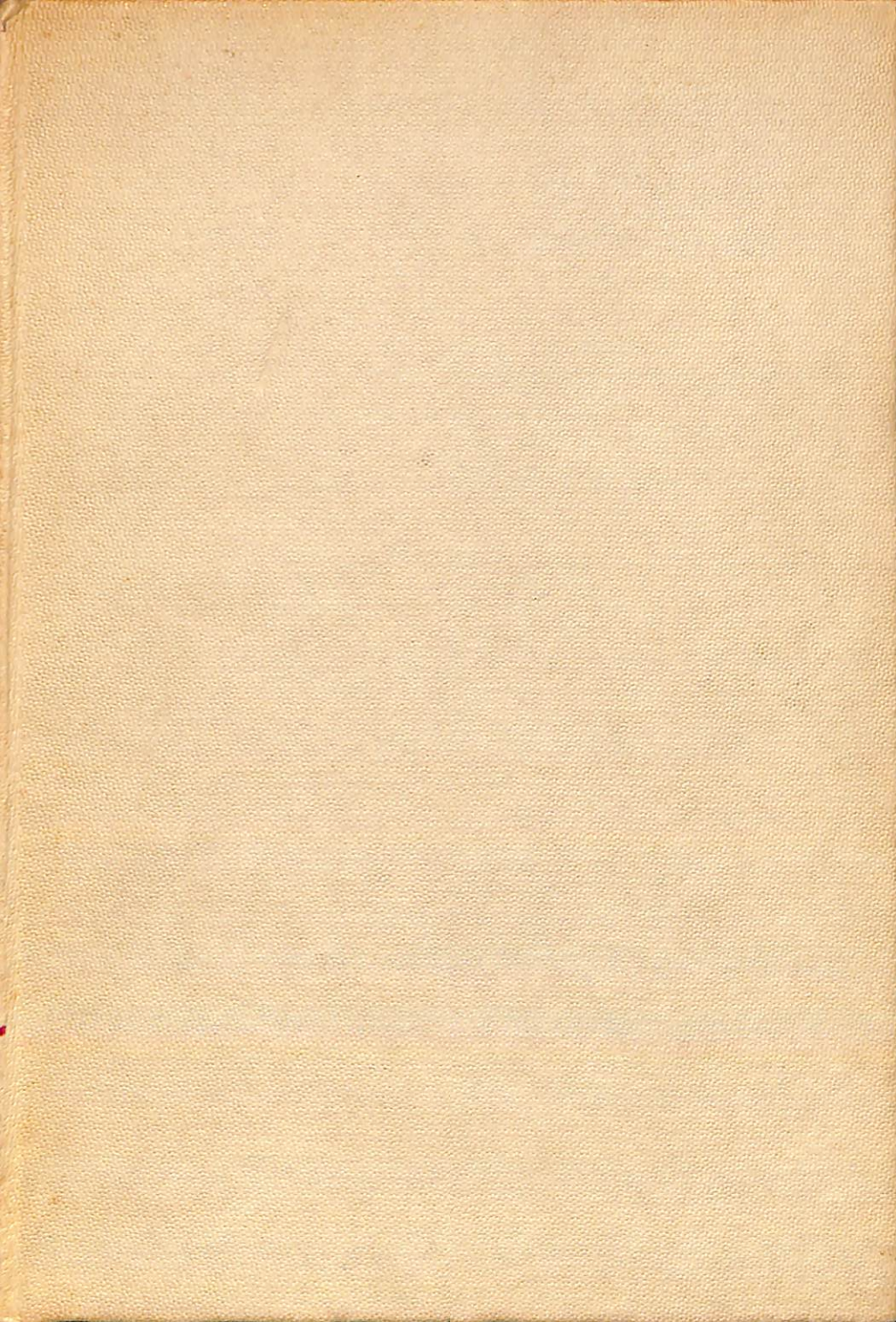
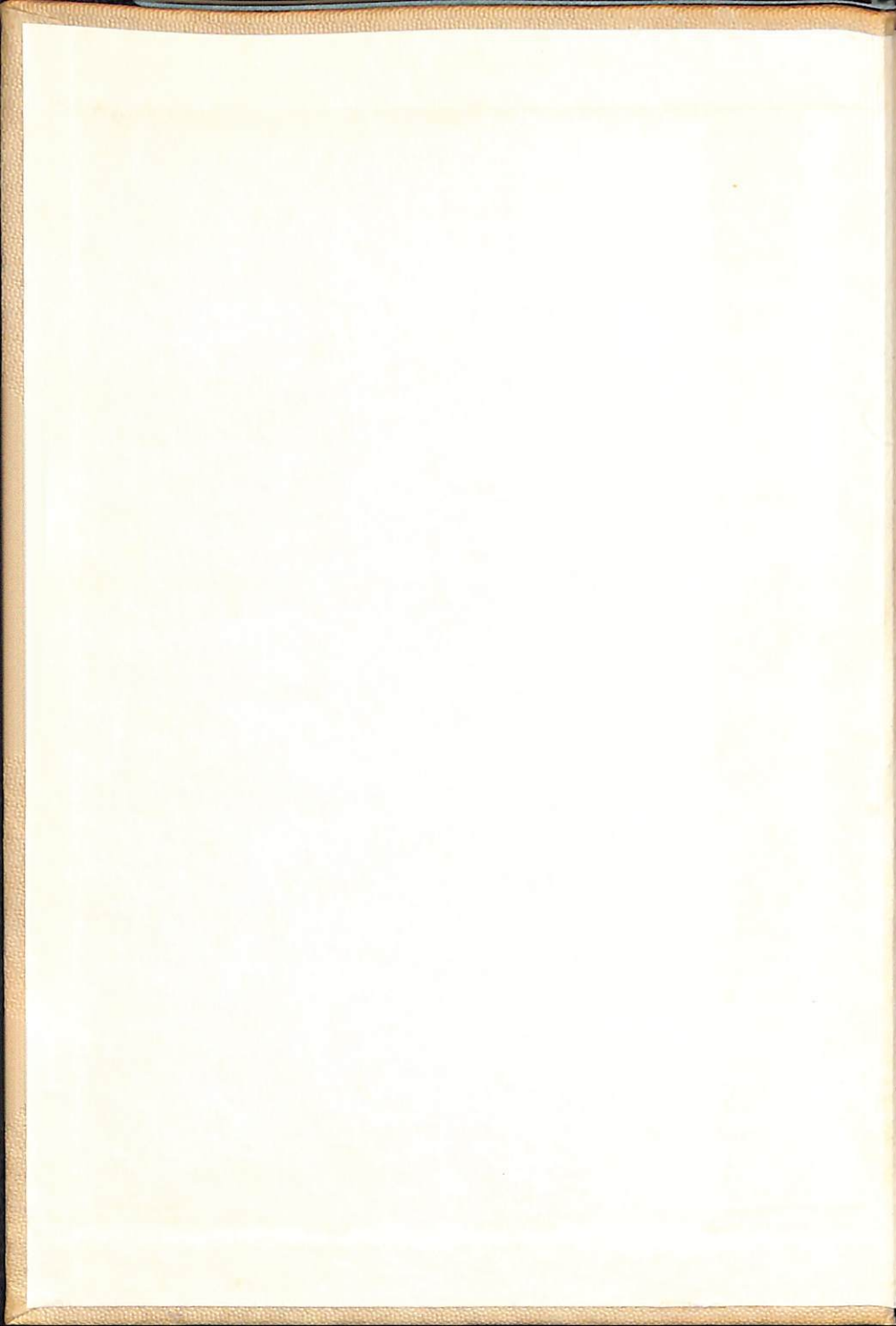






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DIGITAL DATA

Their derivation and reduction
for analysis and process control



DIGITAL DATA

*Their derivation and reduction
for analysis and process control*

by
D. S. Evans
M.I.E.E.

HILGER & WATTS LTD
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PREFACE

My intention in writing this book is to provide an insight into the use of data-handling equipment. Development in the field of data handling is rapid and I have as far as possible chosen instruments and systems that are either in production or have been made in prototype form, but even they are likely to change in detail as techniques and improvements suggest themselves with use and experience. I have therefore given only enough detail to provide a basic understanding of the construction and use of the units and systems. Furthermore I have limited the scope of this book to shaft-driven digital devices with which I have had most experience. There are of course many other basically similar developments, particularly in the U.S.A., and there are a variety of purely electronic analogue-to-digital converters. To describe these would be an enormous task and would probably be confusing to anyone attempting to grasp the principals of digital instrumentation for the first time.

I am very much indebted to my colleagues, past and present, who have been concerned with the development and engineering of these devices and to the directors of Hilger & Watts Ltd, for their patience and encouragement in the development period.

Finally I thank Messrs Napier for allowing me to reproduce the photograph of the programme digitizer (Fig. 25).

March, 1961

D. S. EVANS

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CHAPTER ONE

INCREMENTAL MEASUREMENTS

Present-day industrial, military, and research problems tend to become more and more exacting in respect of accuracies of measurement, number of observations and control points, speed of operation, and correlation of results. This means that the problems have to be solved partly or completely by automatic methods so as not to waste manpower or be subject to human failures.

NUMERICAL EXPRESSION

Generally speaking quantities can be portrayed in three ways:

(i) *Physically* as by the level of a liquid in a manometer, the displacement of a beam, the movement of a pointer, a change of voltage, etc. Such indication is analogue and although associated with a visual scale, the interpretation of the reading is a matter of speculation depending upon the skill, bias, or alertness of the observer. Here man acts as an analogue-to-digital converter to achieve accuracy.

(ii) *Graphically* as by the temperature chart of an automatic pen recorder. This again is an analogue system, since

the height of the curve represents the upward and downward excursions of the temperature. The curve itself is useful because it indicates trends at a glance, but again reference has to be made to the scale if the value of a particular plot is to be derived.

(iii) *Digitally* as by the figures on a bus ticket or the price tags of a cash register. Such figures involve no guess work on the part of the observer; mental calculation is not required no matter how many figures there are. The least significant figure is as clear as the most significant.

These examples must not be interpreted as meaning that the conversion from analogue to digital presentation improves results, since results cannot be more accurate than the indications produced by the measuring device. The examples, however, do show that it is desirable to express measurements in digital form to obtain preciseness of meaning.

SCALING

Absolute values of measurement are mostly expressed in figures, whether they are shillings and pence, pounds and ounces, feet and inches, etc. Mathematical expression can contain an indefinite number of digits, all of which have meaning. However, the number of fractional digits that can be used when measuring physical quantities is restricted because there is a limit to the accuracy of measurement that can be achieved. This limitation is due to one of three factors: the fineness to which a scale can be produced, the drift between the quantity being measured and the media that is used to measure it, and the difficulty to match accurately the non-linear characteristics of the quantity being measured.

Calculable non-linear variables can be measured by linear devices and the result transformed later in the system. The alternative is to provide individual scales with or without correcting devices to produce directly proportional readings. The choice is usually one of economy. If all the quantities are sufficiently similar so that the same non-linear scale can be used, the manufacture of such a scale may be justified, otherwise it will be more economical to use standard linear scales and apply corrections in the final assessment.

The preciseness of any measuring system depends on the stability and accuracy of the detecting element, the transducer (if any), the measuring device, and in analogue systems the power supplies and transmission links.

When considering the introduction of a digital system, inaccuracies caused by uncontrolled variables in various parts of the system must be taken into account. If they cannot be corrected, there is no point in making the digital part of the system more accurate.

WHEN TO DIGITIZE

Many control and recording systems are digital in part or in whole, and there are excellent reasons for most of them. It is conceivable, however, that digitizing may not produce results better than those of a conventional analogue scheme. Digitizing for the sake of it would prove uneconomical in many instances and may not produce anything more than an automatic machine for the generation and tabulation of useless information.

There are probably four main reasons for choosing a digital system, each sufficient justification on its own, though often they are inseparable.

(i) *Accuracy of measurement.* Accuracies of 0.1 per cent are generally accepted as a commercial standard and are not difficult to attain. Much greater accuracies are often possible.

(ii) *Storage and computation.* Digital data can be easily stored and at a later time passed to a digital computer for evaluation.

(iii) *Transmission.* Digital information can be sent by radio or teleprinter link without loss.

(iv) *Presentation.* Data can be presented in figures that are easy to read and can also be tabulated on a sheet of paper.

If the prime motive for digitizing is accuracy, then digitizing should commence as early as possible in the chain of events. If, on the other hand, the aim is to provide a suitable presentation for the human operator or computer, it may be more economical to introduce the digitizing at a later stage when digitizer equipment can be shared.

DERIVATION OF DATA

The method of converting analogue to digital form falls into two main categories.

(i) *Counting techniques.* When the variable quantity is composed of a number of random but distinct elements, such as nuclear particles or peas, the elements may be counted as they pass a given check point. The reference may be time, distance, area, or volume. Sometimes it is convenient to refer quantity when it is not in particle form to an incremental scale and to count the scale's increments. In such an instance, the scales are directly proportional to a given physical quantity e.g. weight. The resolution of the scale may be dictated by manufacturing tolerances. The final count

in any system may run into many millions if so required. The accuracy of the count depends on the speed of response of the counter, there being no confusion (which is caused by hesitation at the check point), and whether individual particles or marks are recognized. Sudden surges in a counting system can be fatal.

(ii) *Scale-reading techniques.* When the quantity to be measured can be referred to a scale, the divisions of the scale may be uniquely labelled. In a scale-reading system, it is not necessary to observe or count the divisions from the starting point. The correct answer will always be available after a supply failure or if the system is switched off between periods of measurement. The question of resolution is again one of subdivision, the accuracy of which is usually limited by mechanical considerations, physical tolerances affecting stability, etc.

SHARING OF EQUIPMENT

Digital systems need not be more expensive than the analogue systems they displace if it can be arranged for the more costly and vital components to be shared. (Examples of such systems will be found on pages 74 and 75). This statement is a generalization which is perhaps dangerous to state, but well worth remembering.

Often it is not possible to share equipment in a counting system unless the time factors are long, because the individual detecting heads have no memories and rely on the information going straight to the counter, though sometimes, for example, magnetic tape memories which have several recording tracks are interposed between the detectors and counter.

In a scale-reading system, several analogue-to-digital converters may share interrogating equipment, time permitting;

here, the converters act as memories giving up the information when called upon to do so.

THE CHOICE OF DIGITAL SYSTEM

In considering the units which go to make up a data-handling system, resolution, speed, and economy of equipment may well dictate the choice of an analogue-to-digital converter, but there are times when the choice is one of personal preference. An appreciation of the individual items with their scopes and limitations, together with an insight into the various ways in which they can be combined to form complete working systems is essential if the best value is to be obtained. For this reason, the author is confining his remarks to instruments with which he and his colleagues are familiar and which are either standard production units or about to become so. However, mention will be made of one or two specials which are worthy of note as an indication of size etc.

CHAPTER TWO

DIGITAL COUNTING DEVICES

THE OPTICAL RESOLVER

The optical resolver is a rotational shaft-driven device transmitting a fixed number of electrical pulses for a given angle of movement. There are many applications for the various types of optical resolvers which are potentially capable of high resolutions. It must be remembered that counting rates become very high if slewing, surging, or oscillating occurs, and these phenomena must be assessed intelligently before deciding on a particular system. The frequency of response of the resolver, the associated circuit, and the counter must be so arranged that miscounts due to the above phenomena do not occur. The correct choice in the right circumstances will produce a simple reliable system. The pulses are obtained from one or more photocells monitoring the light which passes through the slits of a glass scale. There are three scale arrangements; they are:

(i) *Direct line counting.* Where the resolution of the scale is fairly coarse or the diameter large, a photocell observes the passage of individual lines (Fig. 1). The sensitivity of the

photocell and the amount of light that can pass through the small slits determine the practicability of a system.

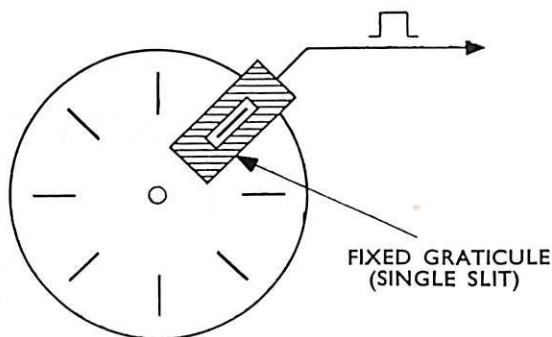


Fig. 1
Individual line detection

On large diameter units of the type shown in Fig. 2 where there are 8,192 lines on one radius and 6,400 on another, the

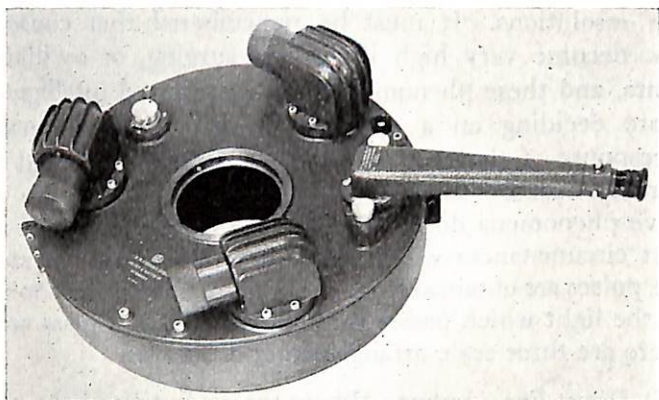


Fig. 2
Special purpose high-resolution optical resolver

slits are only 0.003 inch wide, but there is plenty of space available for fairly large illuminating sources. Such units have been tailored to fit around existing shafts of other equipment and have a large hollow precise centre mounting. Centring adjustments and a viewing microscope are provided for final centring on site. A single mark at a given radius provides a zero reference pulse for each revolution of the disk which carries the scale.

Occasionally there is a need to reduce the size of the optical resolver without changing the order of resolution and

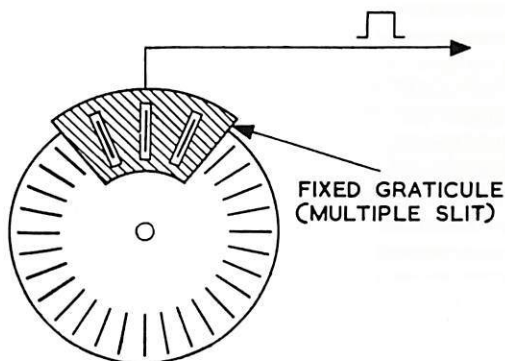
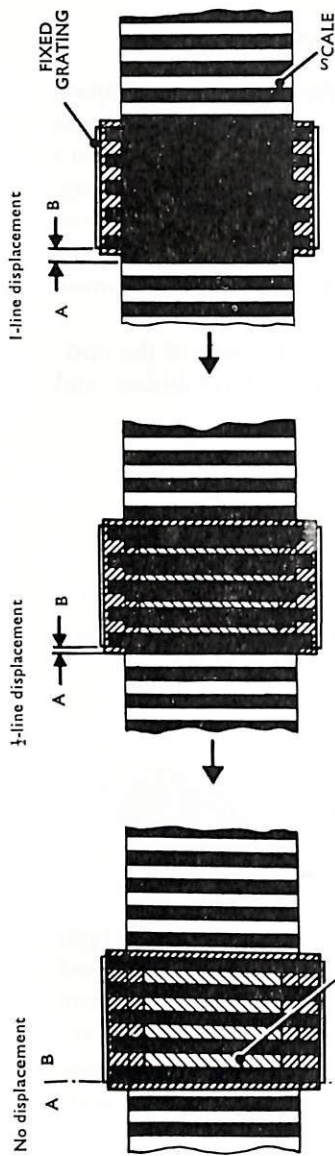
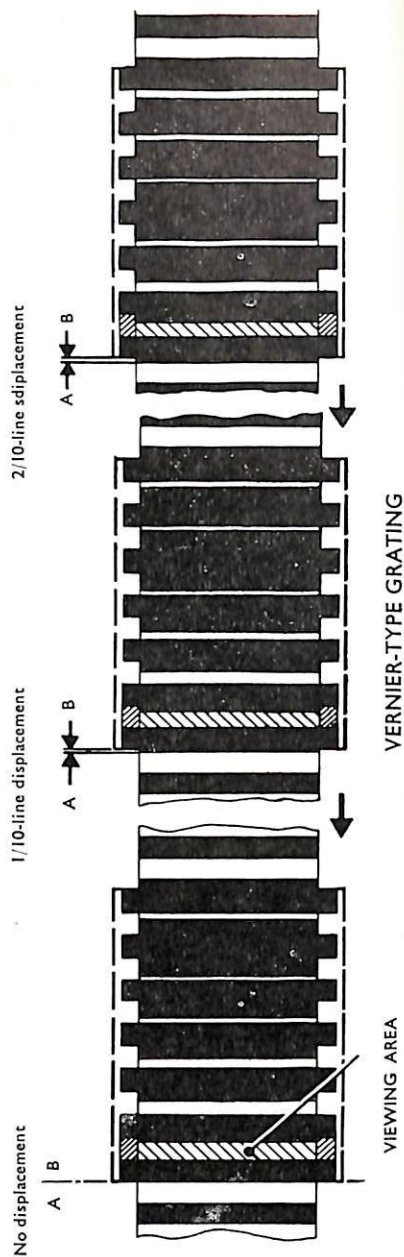


Fig. 3
Multiple line detection

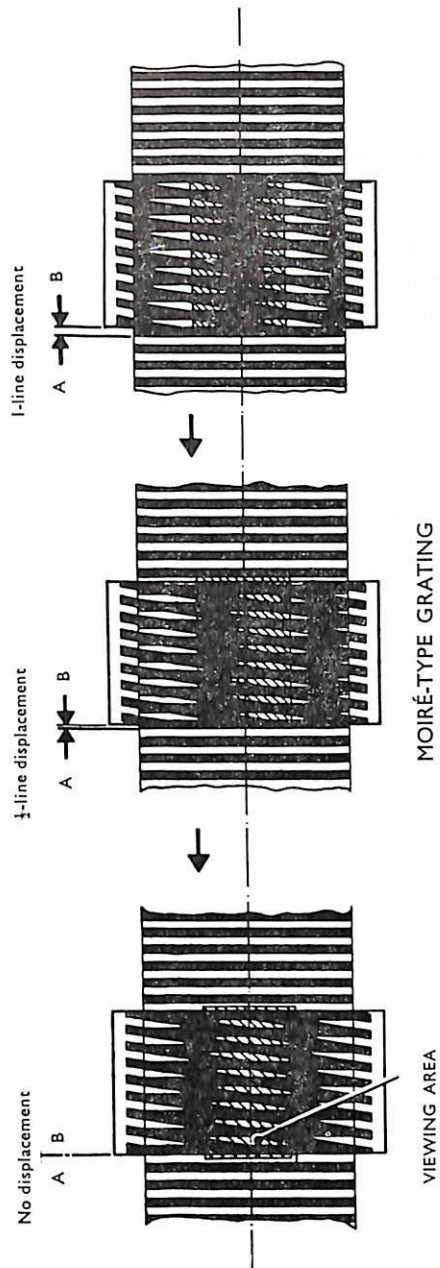
when this is so, the main problem is to obtain sufficient light from the diminished light source to operate a smaller and less sensitive photocell. The easiest solution is to illuminate and observe a group of slits and to use the total light received (Fig. 3). Here the defining window is a shutter-type grating of the same pitch as the slits of the moving scale (Fig. 4).



SHUTTER-TYPE GRATING



VERNIER-TYPE GRATING



MOIRÉ-TYPE GRATING

Fig. 4
Types of optical gratings

(ii) *Vernier fringe counting.* If the line spacing of the fixed grating is different from that of the scale, complete light and dark conditions cannot be obtained over the whole area. The result is an intensity gradient or vernier fringing which appears to travel around the disk as the scale is moved, the fringe pitch or cycle depending on the difference in line spacing between the fixed and moving gratings (Fig. 4). Successive line coincident points may be tens or hundreds of lines apart and this separation is the fringe spacing. One line or slit movement of the scale will produce one fringe movement, giving an effective magnification of the scale movement. The total movement of the scale can be determined by counting the number of fringes that pass a given point.

(iii) *Moiré fringe counting.* A more usual type of grating that produces fringes is one in which the slits are not truly radial, but are tangential to a small circle, the fixed grating being crossed with the moving one. The result is a type of moiré fringe pattern which travels radially towards and away from the axis of the disk depending on the direction of rotation of the disk.

The circular moiré fringes have been put to good use and are of prime importance where high-angular resolution is required in a small space. Apparent magnification of the linear motion is obtained and individual errors in positioning or flaws in the slits are not important because over a great many slits the resolver acts as an averaging device (Fig. 4). The direction in which the fringes move and the scales rotate can be determined by phase discrimination of the output of two photocells spaced a quarter of a pitch apart. If the outputs from both cells are observed, the waveforms squared, and the pulses derived from the leading and lagging

edges of the combined waveforms, four times as many pulses can be obtained as there are lines or fringes in the unit.

The light outputs from these three types of grating are very different for a given displacement of the paired gratings (Fig. 5). The shutter-type grating gives the greatest contrast and is most suited to relatively coarse scales. Both the

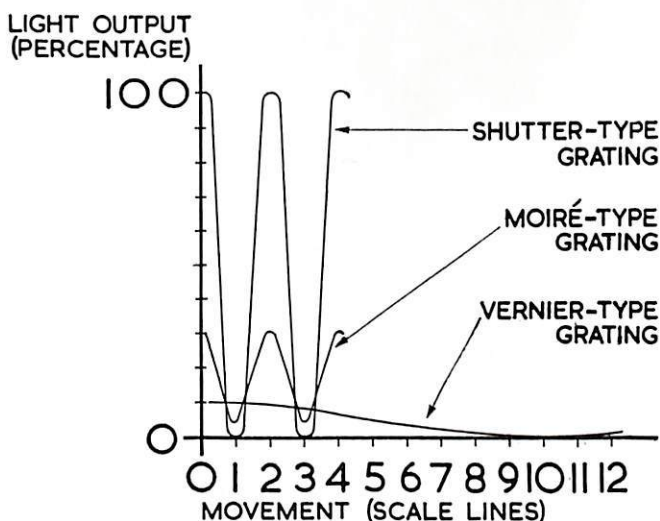


Fig. 5

The relative contrasts for a given viewing area of three different gratings

vernier and moiré-type gratings produce effectively magnified motions, the vernier in the direction of motion and the moiré at right angles to the scale displacement. These two gratings are therefore more useful for high-resolution devices, the moiré-type grating being the most used because

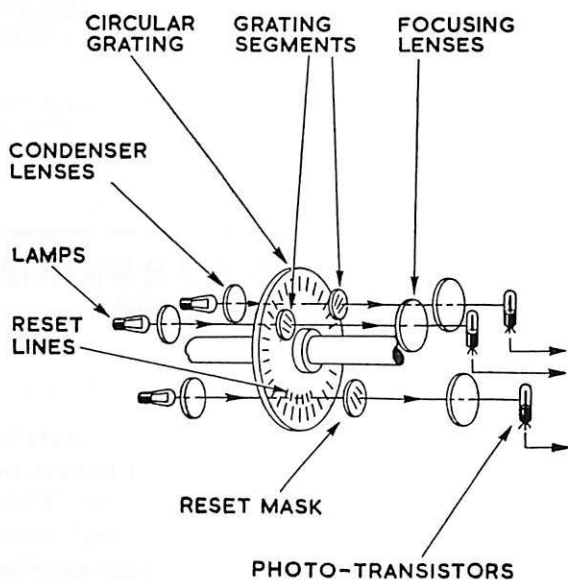
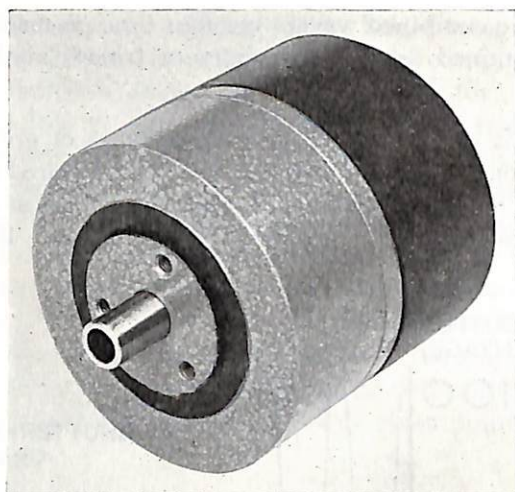


Fig. 6

Optical resolver with two gratings in quadrature and a reset mask

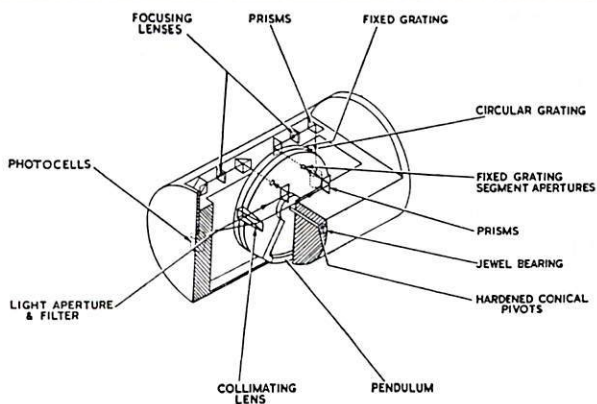
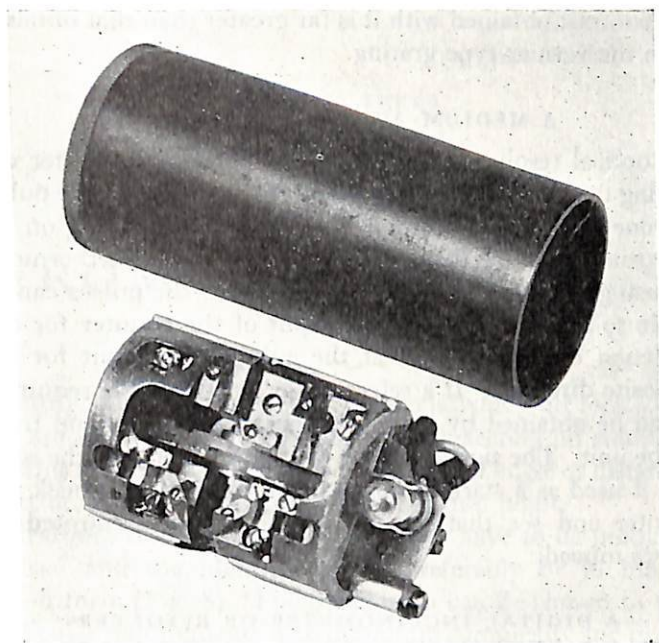


Fig. 7
Digital inclinometer

the contrast obtained with it is far greater than that obtained with the vernier-type grating.

A MEDIUM-ACCURACY RESOLVER

An optical resolver unit (Fig. 6), 3 inches in diameter and having multiple slits, will produce 1000, 2000, or 4000 pulses for one complete revolution, the number depending on the electronic circuitry that follows the resolver. Furthermore, by using a suitable discriminating circuit, the pulses can be made to appear at the adding input of the counter for one direction of rotation and at the subtracting input for the opposite direction. If a reference or zero signal is required, it can be obtained by having a separate photocell and track in the unit. The signal appears only at one place on the scale and if used as a starting mark, it can be made to check the counter and see that no spurious signals are counted or pulses missed.

A DIGITAL INCLINOMETER OR RESOLVER

A good example of the resolution and small size that can be achieved by fringe techniques is the digital inclinometer (Fig. 7). This was specially developed to fit into the nose of model aircraft for wind-tunnel observations. The track radius of the optical scale is only $\frac{3}{8}$ inch and the whole unit fits into a cylinder about 1 inch in diameter and $1\frac{1}{4}$ inches in length. The moving scale of the instrument has a pendulum suspended from it and is constrained from moving more than 5 degrees. The resolution is $1\frac{1}{4}$ minutes of arc, which is equivalent to a complete revolution of 17,280 pulses.

CHAPTER THREE

DIRECT READING FROM CODED SCALES

Carefully divided scales with divisions which all look alike and are unlabelled are described in the section on counting systems (page 7). A count, as a measure of angle or distance, must be made from a given zero or datum point.

In direct-reading systems, the scales have to be uniquely marked and the identity should preferably be in binary on-off form (Fig. 8). The breakdown can be chosen to suit particular requirements with minimum complexity and maximum reliability; the scales can be divided decimally, sexagesimally, binarily, and in terms of any other radix.

The choice of scale length and subdivision is one which is usually dictated by the particular system being considered and no rule can be laid down to cover all requirements. It should, however, be said that the scale ranges, available in standard units, cover a wide field and that generally it is more economical to design a new system based on these than to insist on special scales.

CODE PERMUTATIONS

The coding arrangement of any particular scale is decided by the requirements of the system. Examples of various

systems are given on pages 37 and 70. Several years of experience in the use of coded scales, particularly for industrial purposes, have proved the versatility of a limited number of

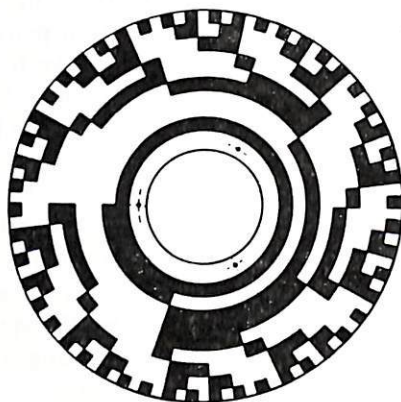
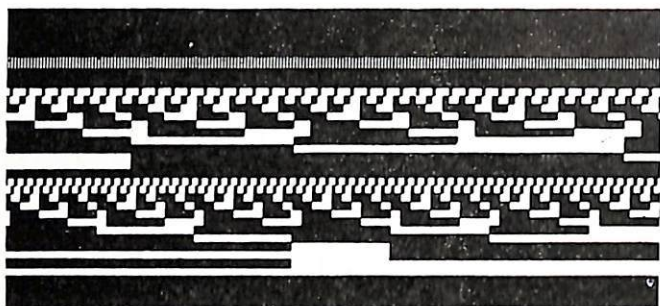


Fig. 8
Binary coded scales

coding arrangements, namely the Cyclic Permuted Binary (C.P.B.) and the Watts Reflected Decimal (W.R.D.). It has therefore been possible to build up a range of digital devices

all using the same codes and also a range of ancillary equipment common to most items (see Chapters Three and Four). One or two special scales, examples of which are given on page 44, have been made; they are neither C.P.B. nor W.R.D.

Figs. 9 and 10 show sections of C.P.B. and W.R.D.

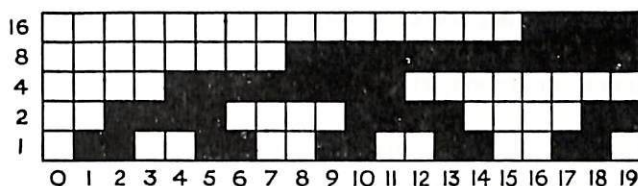


Fig. 9
Cyclic permuted binary code

scale patterns. Examination of these will show that only one digit or horizontal track changes at any one time. Scale

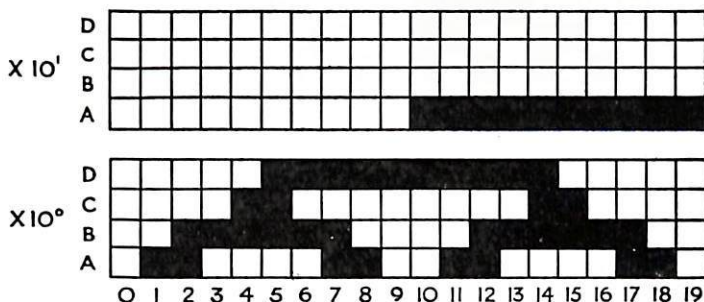


Fig. 10
Watts reflected decimal code

patterns that provide this feature are cyclic and the rise and fall of the patterns can be seen as back-to-back reflections.

For instance, in the units decade of the W.R.D. 10 to 19 is the reverse of 0 to 9 and if the tens decade is disregarded the scale will read 0 to 9, 9 to 0, 0 to 9, 9 to 0, etc. The same is true for the C.P.B. except that the cycle is much more rapid. The finest track reads 01, 10, 01, 10, etc. These reflections appear on every track, but they become less frequent as the scale becomes coarser. In fact the groups of 1's and 0's double in number for each successive track, e.g. the second track reads 0011, 1100, 0011, 1100, etc. and the third reads 00001111, 11110000, etc.

DECODING

To decode C.P.B. and W.R.D. codes, a simple inversion rule can be applied. The readings of the higher tracks determine the way in which the lower tracks are translated. The

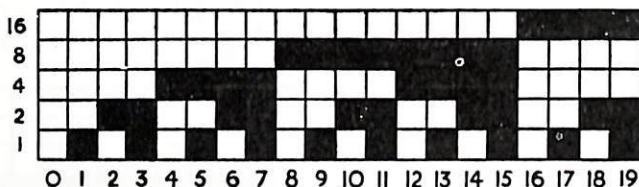


Fig. 11

Pure binary code

Black squares represent 1. White squares represent 0.

inversion rule is applied line by line for the C.P.B. and for the W.R.D. it is applied decade by decade or line by line. Starting therefore with the top or slowest changing track of the C.P.B., if the result is odd (1) the next track value has to be inverted, i.e. 0 for 1 and 1 for 0. If, however, the first track is even (0), the second track is left as read, i.e. 0 for 0 and 1 for 1. Again, if the resultant reading of the second

track is odd, the third track reading is inverted and so on. When an odd is changed to an even the line below is not inverted and when an even is changed to an odd the line below is inverted. The result of applying this rule to the pattern of Fig. 9 is the pure binary (P.B.) pattern of Fig. 11 where each track or digit can be given a definite numerical value (in this instance 1, 2, 4, 8, etc.).

In Fig. 12 a small section of a C.P.B. scale is shown connected to a relay tree. The purpose of the relay tree is to

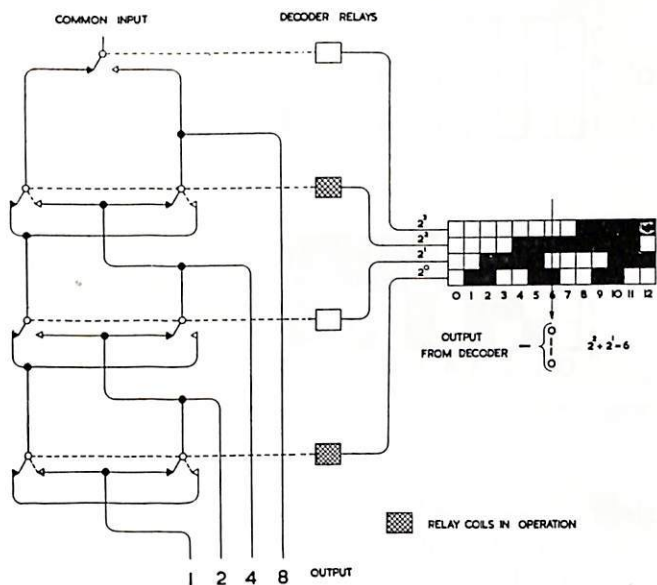


Fig. 12
Relay circuit for converting C.P.B. to P.B. code

translate the scale to ordinary binary. The detector for each track of the scale operates a relay which acts as a reversing

switch. The relay contacts are pulled over when the detector is on a shaded sector of the scale. In the example given, it is assumed that the detectors are ranged in the position indicated by the arrow so that the relays 2^0 and 2^2 are energized. Following the circuit from the common input, the outlets will appear in the order 0110 or $2^2 + 2^1 = 4 + 2 = 6$. The circuit obeys the inversion rule for rectifying cyclic codes.

Using the line-by-line inversion rule on the W.R.D. code produces the pattern of Fig. 13 where again the digits can

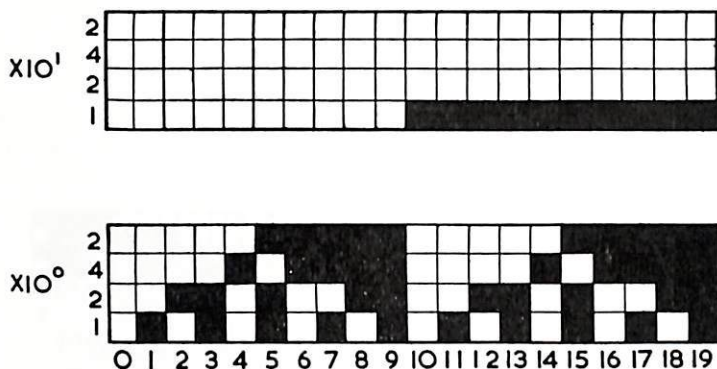


Fig. 13

1, 2, 4, 2, code derived from the W.R.D. code

be given numerical values and summed decade by decade. The summing of the digits can be very useful, for example, in a high-speed scanning system; but in a parallel decoding system using a relay tree, it is usual to treat each binary quartet or decade as an entity. In other words, if the first or more significant decade is odd, the second decade is rectified or complemented by inverting the D track and so on, the result being the repeating pattern of Fig. 14. This is an

extremely easy thing to achieve since the only change required is the inversion of the meaning of the D track or

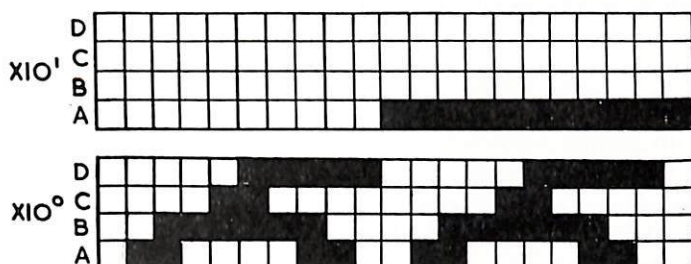


Fig. 14
Rectified W.R.D. code

complementing digit. Here the result is a ten-line output for each decade.

Fig. 15 shows a suitable relay tree arrangement for decoding one decade of W.R.D. It can be seen that the inversion

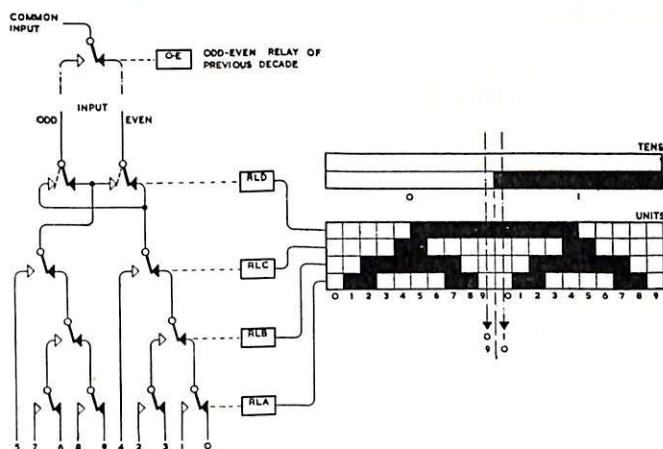


Fig. 15
Circuit for decoding W.R.D. to decimal

of the D relay contacts depends on the point of entry which is determined by the odd-even or odd indicating relay operated from the previous or more significant decade.

AVOIDING AMBIGUITIES

With simple non-cycle binary coding arrangements similar to those of Figs. 11 and 13, where more than one digit change occurs simultaneously, ambiguities are avoided in parallel reading systems by 'choosing'. All the detectors or reading heads are duplicated and the two sets read alternately in such a way that no reading is ever taken from detectors on or near the boundaries of each division of the scale. It is generally considered that there is no justification for using this procedure with coarse single-scale linear or rotational digitizers, but with multiturn digitizers (and linear equivalents) where backlash is involved there is good reason (which is explained on page 38) for adopting it.

BASIC SCALE ARRANGEMENT

There are several ways of scaling, but by way of illustration only two fundamental forms will be described here. These two forms are loosely termed mechanical and optical and may be circular, rectilinear, or cylindrical in shape. Mechanical scales are of metal and have insulating sectors arranged so that the binary digit 1 is a conductor and 0 an insulator (Fig. 16). These sectors are detected by electrical contacts, one bearing on each of the tracks of the scale. Optical scales, on the other hand, are usually made of glass (Fig. 17), but may be of mica or perspex; they have coatings of photographic emulsion or metal and give clear and opaque sectors in the pattern arrangements already described. The digits

may be so arranged that the 1's are clear or opaque. The scales are illuminated on one side and the light that passes



Fig. 16
Metal coded scale



Fig. 17
Glass coded scale

through is picked up photoelectrically. Various arrangements available commercially will now be described.

THE MECHANICAL DIGITIZER

The mechanical digitizer (Fig. 18) comprises a flat metal scale $4\frac{1}{2}$ inches in diameter, which (in the latest models) is carried on a hollow shaft; the shaft runs in ball-bearings carried in a hollow rotatable shaft. The scale is extremely accurate and the contact surface is made flush and flat within tight limits. Spring-loaded contacts are positioned accurately so that they rest on the individual tracks of the scale. The maximum number of divisions normally obtainable on this size disk over 360 degrees is 1000 in W.R.D. code and 1024 in C.P.B. code.

A unit of this sort is simple in concept and because it can be fed directly into a relay decoding unit, it provides a fairly cheap data-handling system. This is particularly so if the decoder can be shared between several mechanical

digitizers. It must be remembered, however, that a multi-contact device of this sort requires periodic attention and should not be relied upon as a monitor in highly critical positions. Inductive loads must not be switched by the

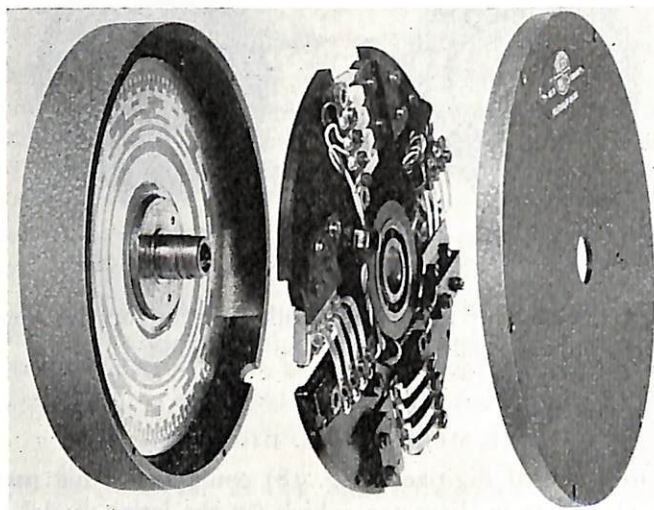


Fig. 18
Mechanical digitizer

disk itself, for if they are, arcing will occur and the tracks will be burnt. To stop this from happening, a buffer amplifier should be used in each line or the supply should be left off until the disk is at rest.

OPTICAL DIGITIZING TECHNIQUES

The demand for greater accuracy, longer life, and extreme reliability for units which supplement or do the work of man and which have to be left for long periods without supervision, can now be met by using photoelectric instruments.

During the last fifteen years serious development of optical and photoelectric digitizing techniques has been carried out. A number of special devices have been used and described. Some of these were of high resolution and though cumbersome were none the less a feat of precision engineering and a big advance in automatic measuring. The experience gained in the manufacture of suitable digital scales, the advent of new photocells, the progress of pulse techniques, and so on have culminated in much more elegant instruments which can be applied to present-day problems in scientific and industrial installations.

THE NEON OPTICAL DIGITIZER

Probably one of the most useful devices to appear on the market for general use is a shaft digitizer (Fig. 19), 3 inches in diameter and of medium resolution. Normally it is provided with a 1000-division inverted W.R.D. scale or a

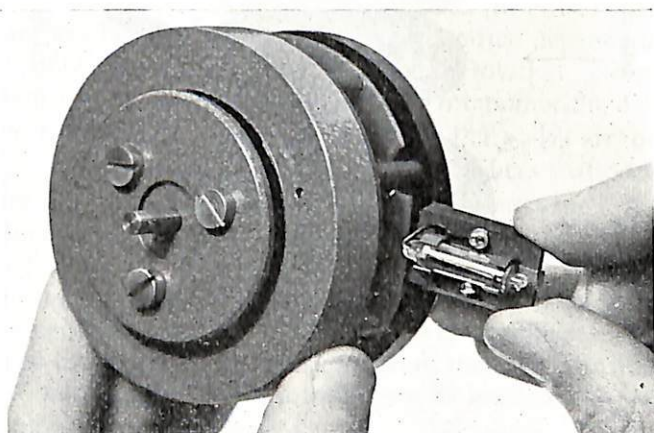


Fig. 19
Neon optical digitizer

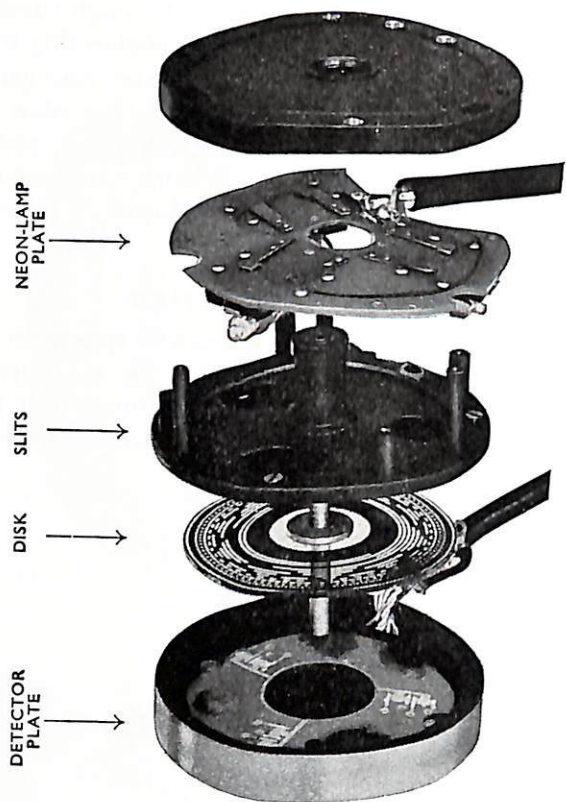


Fig. 20
Exploded view of a neon optical digitizer

1024-division C.P.B. scale. It is possible for the instrument to have as many as 4000 divisions.

The photocells are Schwarz cadmium-selenide cells in pellicle form (Fig. 20) and are mounted on a printed circuit plate. There is one cell for each track of the scale, so that a thousand-division scale will have four for each decade, making twelve in all. The dimensions of the digitizer are such that the cells have had to be divided into three groups of four, and so there are three radial defining slits co-operating with the three cell groups. The tracks of the scales are staggered to suit this arrangement.

The cells, like other semi-conductors, are subject to drift when the temperature changes and to avoid this deleterious effect an a.c. system employing a cold light source is used. The recommended maximum ambient temperature is about 45°C and if this is exceeded the cells will still function, but the outputs will be reduced.

Two neon light sources which can be a.c. (or pulse) operated are available. The choice of light source depends on the speed of read-out required and on the resolution. Normally the speed is dictated by the speed of rotation or the digit change rate during read-out. Although the scales are not ambiguous in themselves, confusion of numbers will occur if more than one scale division or number passes the detectors during the read-out period. This is true of any system.

For fairly slow rotating shafts where the division transit time is at least 2 milliseconds, small conventional neon lamps can be used (Fig. 19). A flash duration of 2 milliseconds is required to produce a usable signal from the cells, but must not be repeated for about 40 milliseconds because the cells must have time to recover.

For digit rates between 0.5 and 2 milliseconds the signals obtained from the normal neons are too small to be manage-

able. A high-intensity neon flash tube (Fig. 21) is available; it is triggered via a pulse coil from a high-voltage supply. The signals obtained have a very steep front and rapid initial decay, so that above a given amplitude the pulse output is of short duration.

With pulse operation, using either type of light source, the repetition rate is limited by the recovery time of the

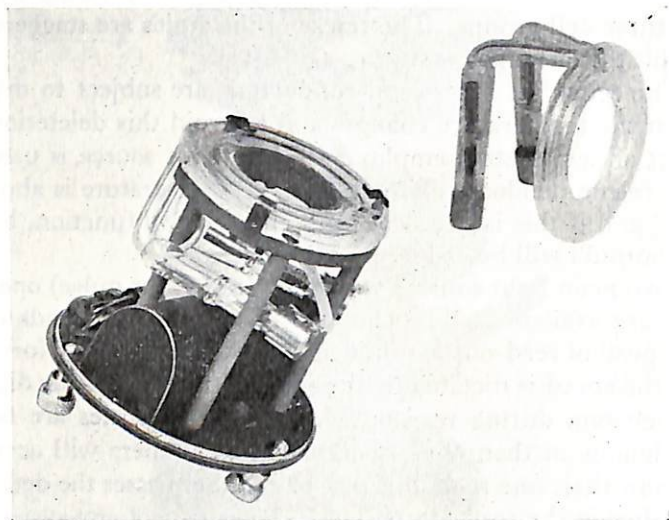


Fig. 21

High-intensity neon flash tube used with Schwarz cells

cells. This is about 40 milliseconds, but for most systems this is more than adequate. Usually the outputs are stored after amplification until the recording medium, which may be a printer, punch, etc., has completed its operation.

SILICON-CELL OPTICAL DIGITIZER

The silicon-cell optical digitizer (Fig. 22) being about 5 inches in diameter is a larger unit than the Schwarz cell digitizer. A reduction in the sensitivity of the cell and the consequent need for a higher intensity light source to obtain comparable outputs are responsible for the increase in size.

Silicon cells are photo-voltaic, i.e. they generate a current when exposed to light and do not require a voltage source. They have a low output impedance and are very suitable for use with transistor circuits. They are chosen



Fig. 22
Silicon-cell optical digitizer

because of their wide temperature characteristics and because their fast response is suited for use with high-resolution or fast-moving scales.

Since the cells will operate at fairly high ambient temperatures, it is possible to use a simple filament lamp as the source of light, and with this type of source the outputs of the cells are d.c. If the outputs are large enough, simple

d.c. amplifiers can be employed, otherwise it is necessary to use chopper-type d.c. amplifiers operating continuously or in sampling mode. Alternatively, to obtain a short sampling time and to reduce temperature effects which are unavoidable with filament lamps, high-intensity flash sources can be used.

THE DRUM-TYPE OPTICAL DIGITIZER

The drum-type optical digitizer is a variant of the silicon-cell digitizer. It has the same cells, a filament light source, but in place of the flat glass disk there is a hollow drum with a clear and opaque linear scale wrapped around its outer circumference (Fig. 23). The light source and the detecting

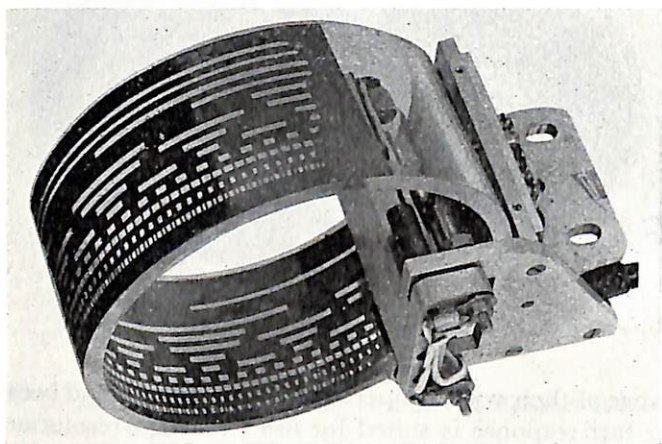


Fig. 23
Optical drum digitizer

heads are shown mounted on the two limbs of a U bracket, and between these two limbs runs the drum which carries

the scale. The supporting drum is made of transparent perspex so as not to interrupt the passage of light through the scale.

The angle subtended by any given length of scale will depend on the radius of the drum and, therefore, only a limited number of master scales need be made to cover a very wide variation in scale ranges. As the drum and reading head are unattached, the drum can be fitted directly to the user's driving spindle thereby introducing no extra friction. The drum is balanced when it is fitted to the spindle and the reading heads are bolted to the frame of the instrument. Such a device is useful where many scale ranges are required on a particular instrument or where balance is likely to be affected by additional friction.

THE PROGRAMMED SCALE DIGITIZER

Sometimes there is a need to know precisely when a shaft has rotated through certain angles, the intervals between these points being of no consequence. The location of each line may be very precise compared with the number of divisions in a revolution. Fine radial slits or fiducial lines (Fig. 24) are accurately positioned around a glass reference scale and are detected as they pass a fast response photocell, such as a silicon solar cell. To distinguish one line or reference angle from another, a continuously coded optical scale is coupled directly to the shaft carrying the radial-line reference scale, the detectors of which may be cadmium selenide or silicon. The coded scale is only read off when a signal is received from the detector after a radial line has passed it. This method is not restricted to circular scales and is represented linearly in Fig. 24.

THE ROLL-ANGLE TRANSDUCER

A programmed scale digitizer (Fig. 25) has been developed

for determining the roll of an air-craft model in a wind tunnel. It is about 1 inch in diameter and $2\frac{1}{2}$ inches long. The shaft carries a circular scale which has 80 radial slits and these slits are 0.0001 inch wide and are detected by a silicon cell. Attached to the shaft is a hollow perspex drum carrying an 80-division binary coded scale. A set of Schwarz cells mounted in a single line along the drum reads the scale.

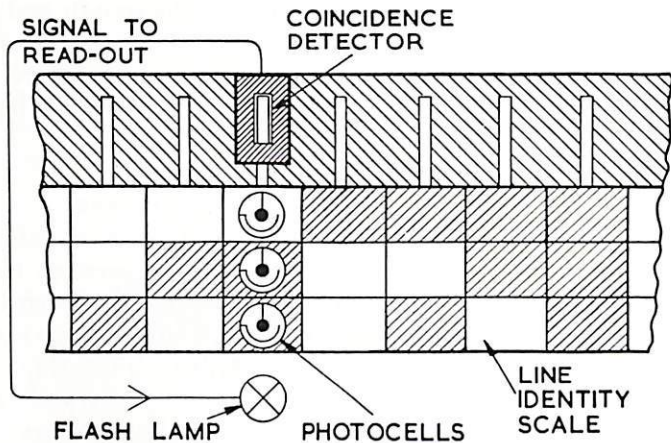


Fig. 24
A programmed scale

Inside the drum there is a neon lamp which flashes on for about 2 milliseconds when a signal from the reference scale is obtained. This information or identification is recorded together with the precise period of the angular rotation, so that it can be correlated with other phenomena of the test run. The coded scale is only read in the middle of the division and so the scale need not be precise or cyclic since ambiguities due to edge errors never occur.

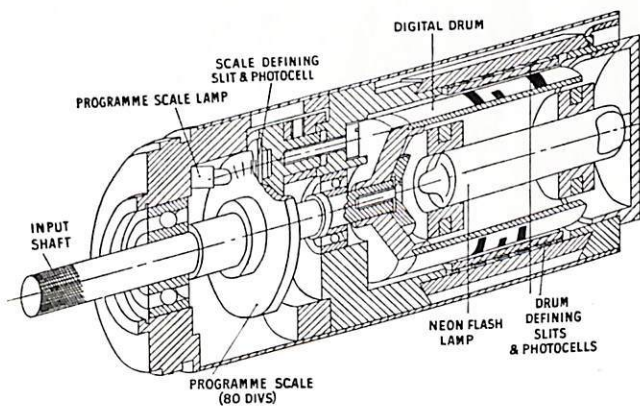


Fig. 25
Roll-angle programmed scale digitizer

HIGH-RESOLUTION OPTICAL SCALES

Optical digitizers have been made with resolutions of 8,192 and 10,000 divisions. Such digitizers are about 5 inches in diameter and have silicon cells and a filament or high-intensity-flash light source. In this type of digitizer (Fig. 26) there is an optical system which magnifies the scale about five times and projects it on to an array of photocells; this

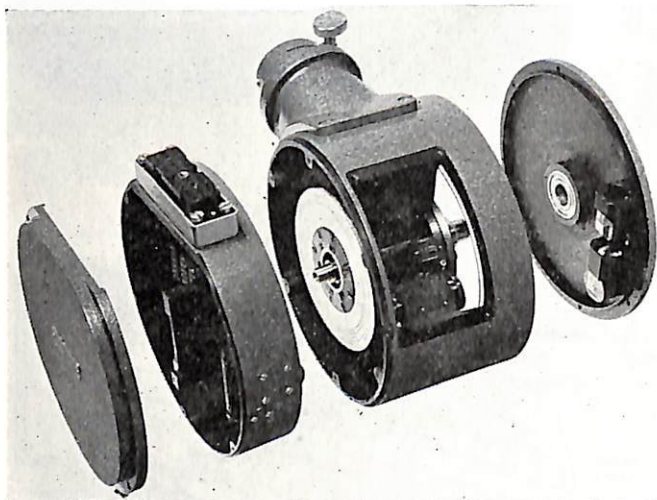


Fig. 26

High-resolution multiturn optical digitizer (8192×32)

results in an increase in the mechanical tolerances of alignment of slits and photocells, and a reduction in eccentricity errors because reading off is at one point on the circle instead of several points around the circle as in mechanical and Schwarz cell digitizers. The light source is reduced to a single lamp and concentrates the light where it is required.

EXTENDED SCALES

Often there is a need to extend the scale range or length without changing the resolution or division size. If, for example, a circular digitizer with 1000 divisions per revolution is attached to the end of a lead screw of 1-millimetre pitch, readings representing 0.001-millimetre (1 micron) steps of the nut or table are given for a distance of 1 millimetre (Fig. 27). This process can be repeated. To identify the millimetres, a second digitizer can be so geared to the first digitizer that it only moves on one division for each

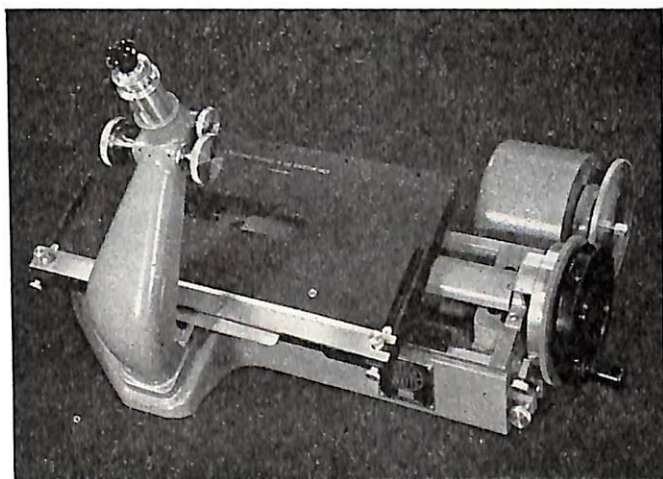


Fig. 27

A measuring microscope with digital read-out to 1 micron.

complete revolution of the first. In other words, coarser or higher figures have been added as in a mechanical counter or cyclometer (Fig. 28), the main differences being that the digitizer's movements are smooth and not stepped and that the direction of rotation can be changed.

Precautions have to be taken in a geared system to ensure that backlash and gear errors do not affect the readings. All the figures have to change simultaneously as, for example, from 999,999 to 000,000, otherwise ambiguous readings will result at the multi-change-over points. Such errors are avoided if the first digitizer controls the changes

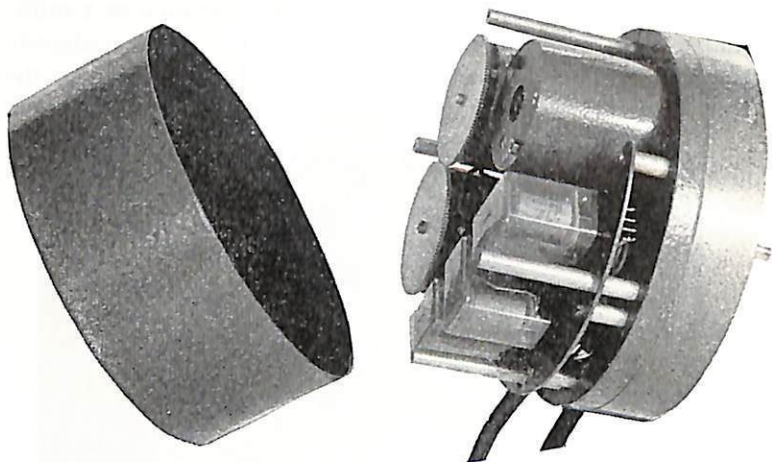


Fig. 28

A combined single and multiturn mechanical digitizer assembly
(1000 × 10 × 10 × 10)

in the second and the second controls the changes in the third etc., so that all changes are effectively decided from the finest 9-0 change-over. Binary digitizers are treated in the same way, but choosing will be at 0-1, 0-8, 0-16 or some other convenient power of two.

THE MULTITURN MECHANICAL DIGITIZER

Multiturn mechanical digitizers (Fig. 29) are small 10-division (decimal) or 8-division (binary) digitizers with two sets

of contacts, one set being spaced half a division in advance of the other. The contact sets are known as leading and lagging brushes because, when their unit is coupled to a fine digitizer, it is phased with its contacts in advance of and behind the contacts of the fine digitizer. The fine digitizer decides which set of contacts is to be read and it makes the change every half revolution. The gear ratio between fine and coarse scales is chosen to maintain the relationship between the divisions of the two digitizers. Whenever in a decimal system the fine digitizer is near the 999-to-000 change-over point, the leading and lagging brushes of the multiturn section are straddling a boundary between

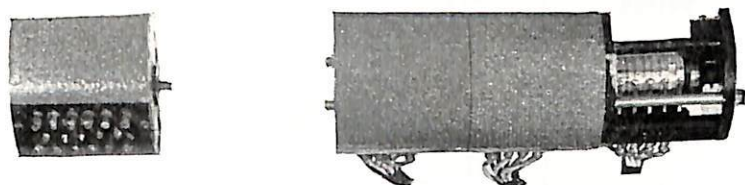


Fig. 29

Multiturn digitizers in echelon ($10 \times 10 \times 10$)

two numbers (Fig. 30). In this arrangement when the fine digitizer is reading 999 (or any number down to 500) the lower figure (i.e. that of the lagging brushes) is read and if reading 000 (or any number up to 499) the higher figure (i.e. that of the leading brushes) is read.

If a scale is to read from 0000 to 9999, then a one-thousand-division digitizer is made to drive a single ten-division multiturn digitizer and this is normally expressed as 1000×10 . To read 999,999, three multiturn digitizers are added, each driven through a one-to-ten reduction gear from the

previous one. This is referred to as a $1000 \times 10 \times 10 \times 10$ multiturn digitizer (Fig. 28); it is a one-million-division scale, but its resolution is still only one part in a thousand of a single revolution of the driving scale.

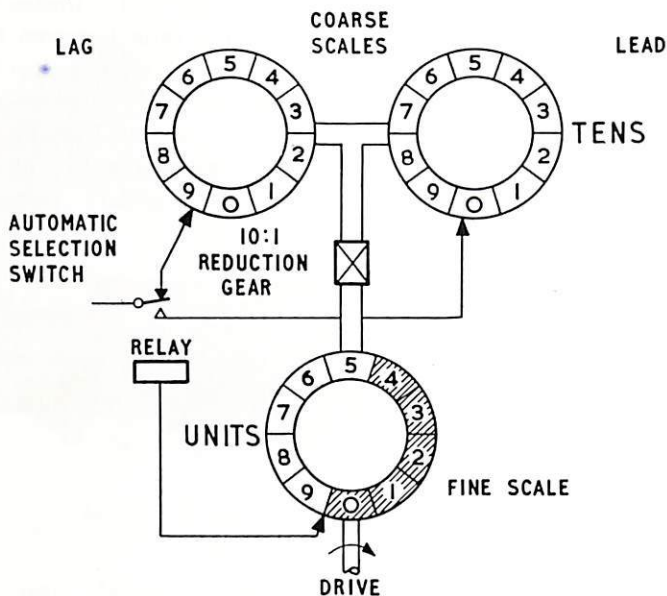


Fig. 30
Avoiding ambiguities due to backlash in geared systems

THE OPTICAL MULTITURN DIGITIZER

The basic requirement for avoiding ambiguities due to backlash in multiturn operations is the same as for mechanical digitizers. Obviously the design has to be different and depends on whether a Schwarz or silicon cell is used.

The leading and lagging defining slits of the optical multiturn digitizer (Fig. 31) are spaced half a division apart in the same way as the duplicate brushes are spaced in the mechanical multiturn digitizer. When the optical multiturn digitizer has separate light sources for the two slits, selection is by switching on the appropriate lamp when a signal is received from the fine digitizer. In such a unit there is no need to duplicate the cell banks provided they can see the light from either slit. If the slits are straddling a boundary on the scale

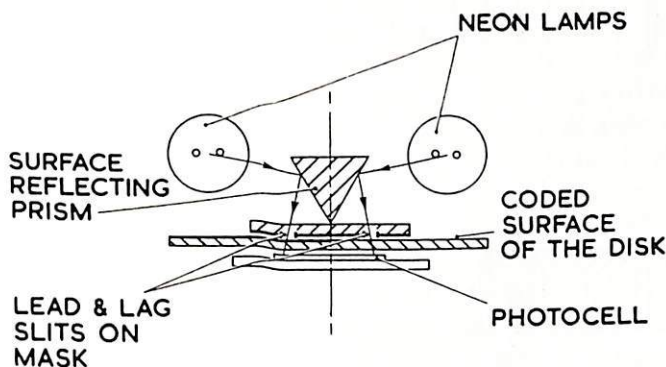


Fig. 31
Multiturn optical digitizer with choosing slits

when the lights are switched, the readings will be changed. The Schwarz cell multiturn digitizer uses this method; it has neon lamps and switching is very fast.

Unfortunately the method is not suitable when silicon cells are used with a filament light source because the lamp response time is too slow for most applications. To overcome this slowness, the cells and slits are duplicated and all the cells are continually in operation. Each cell has its own

transistor amplifier and choosing is done by impulsing the appropriate set of amplifiers. This does not affect the very fast read-out rate.

BREAKDOWN SCALES

Very high resolution scales are difficult to make free of blemishes and touching up becomes costly and impracticable if all the binary digits are laid down as on a standard scale. The finer sections of a scale are repetitive, and so it can be

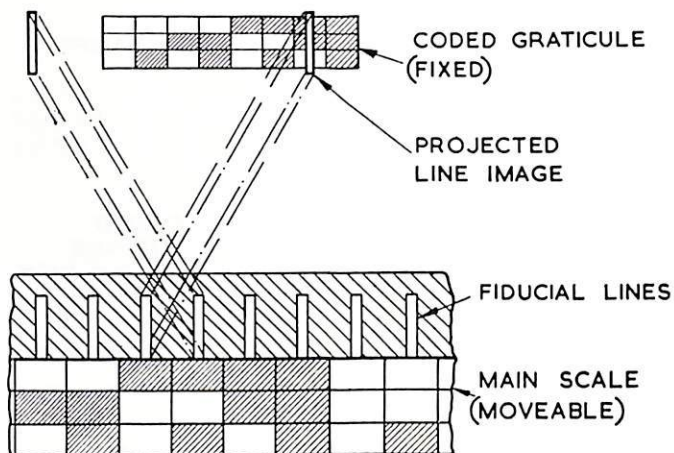


Fig. 32
Breakdown scale arrangement

arranged to omit these entirely from the main scale and substitute them for a separate graticule which carries only one cycle of this information. Not only can the number of marks or digits be drastically reduced, but the graticule can be magnified so that the individual marks are proportionately larger than those on the main scale (Fig. 32).

In a practical system, the main scale is the one that moves and is the measuring medium. It must therefore carry the critical divisions or fiducial marks, each mark being labelled in code. These marks appear as clear radial slits exactly positioned and equally spaced around the periphery or along the length of the scale depending on whether the scale is circular or linear. The width of the projected slit image should be less than the smallest effective division of the graticule.

The graticule is so positioned that the magnified images of any two adjacent lines of the main scale just straddle the graticule. As the scale moves only one slit image at a time passes over the graticule and as one image leaves the graticule another appears at the opposite side, and so there is always continuity of reading. By scanning along a slit image at right angles to the length of the graticule, a single photocell picks up the information track by track and transmits it serially. Alternatively, individual photocells for each track of the graticule can be made to give parallel read-outs.

The coded divisions on the main scale are merely to identify the fiducial lines. The tolerances of this section can however be considerably eased by treating it in the same way as a coarse section or sections of a multiturn digitizer and choosing from the results obtained from the graticule.

LENGTH MEASURING SCALES

The coarser range of digitizers for measuring shaft rotations are normally in circular form. These circular digitizers have many applications and are used in various ways to represent an infinite variety of linear as well as angular motions to quite high accuracies. Their linear counterparts are not so common because it is difficult to finalize on standard ranges for

linear scales, since each one has to match the particular problem in its length, resolution, subdivisions, and materials.

Linear scales to very high orders of accuracy come into their own in situations where gearing and other mechanical means of translating to rotary motions cannot be used. In general the coding and detecting techniques are no different to those used in circular equivalents. Though the applications may be different the ancillary units are often the same, and so there is no need to make further reference to linear scales.

FUNCTION SCALES

Whilst the majority of scales represent functions such as length or angle, sometimes there is a need to have scales for sines, square roots, logarithms, etc. Such scales have been made for special projects. Linear function scales with non-standard breakdowns and coding have also been made, such as those representing sugar degrees, and time.

UNCODED DECIMAL DIGITIZERS

Ten-division multiturn mechanical units requiring no decoding are sometimes used with finer coded optical or mechanical digitizers, but they can be used separately as remote recording counters. When applied in the right circumstances they can effect an economic saving of ancillary gear.

The rules for avoiding ambiguities on individual scales and between sections are the same as for the coded versions and need no further amplification. A choosing system (Fig. 33) selecting odd and even number-contacts alternately is used. One relay switch avoids ambiguities on any particular scale, and a second relay or switch (not shown) prevents ambiguities due to backlash between two scales.

The decimal digitizer is basically a single-pole ten-position

selector switch with a bridging-wiper contact. A second bank or track operates a relay for alternate positions and is known as the odd-even contact. In operation the decimal track will connect two adjacent contacts, but the decision to switch

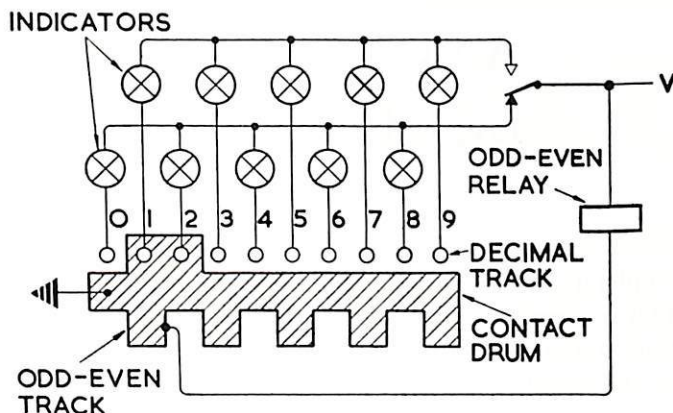


Fig. 33

An uncoded decimal digitizer arrangement

over is determined by the odd-even contact. This arrangement ensures that only one circuit is determined at a time and that there is no break between the changes as in a conventional non-bridging-type wiper.

To avoid passing heavy inductive currents through the scales, it is advisable to operate buffer stages, one for each of the ten outputs. These can be shared between several digitizers when each digitizer can be selected in turn. This arrangement is very suitable for operating typewriters, card punches, etc. For visual display using low-wattage lamps, there is no need to interpose a buffer stage. Sparking, if any, occurs across the relay contacts, there being no switching by the drum itself.

CHAPTER FOUR

ANCILLARY EQUIPMENT

To understand the various arrangements reviewed in the chapter on applications, it is necessary to give here some information about the individual components of the systems to be discussed.

UNI-DIRECTIONAL COUNTERS FOR RESOLVERS

There are on the market several electrically operated conventional counters, for example, the solenoid actuated mechanical counter, the Dekatron counter, and the valve or transistor scaler. Any one of these will count pulses obtained from the single output of a simple optical resolver. The choice of counter depends on the counting rate, whether the code is decimal or binary, whether the counter is automatically resettable or not, etc.

In most instances it will be necessary to insert an amplifier and a pulse shaper into the system before the counter. The design of the circuitry depends on the particular resolver and counter in question and the modes of operation, and so this is left to the engineer in charge of the system or the counter manufacturer to work out.

DIRECTION DISCRIMINATOR FOR RESOLVERS

A direction discriminator is only required when resolvers which give two separate outputs in phase quadrature are used. The two phases determine whether the counter counts up or down according to the direction in which the resolver shaft rotates.

Fig. 34 shows the idealized wave forms that determine rotation. The signals obtained from each of the two photocells are approximately sinusoidal and 90 degrees apart. The

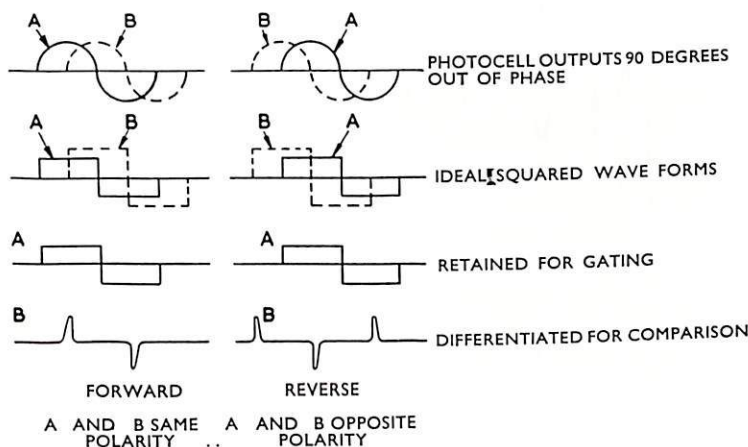


Fig. 34

Direction discrimination from two detectors 90 degrees apart in an optical resolver

positive (or negative) waves are squared in the discriminator and one phase is differentiated to provide positive (or negative) pulses off the leading and lagging edges of each square pulse. Depending on the direction of travel, the differentiated signal will appear opposite either a high or low signal

of the opposite output. By using the square wave as a gate, the pulse can be made to appear on one of the output lines from the discriminator.

Making the circuit more involved and applying the same principles, it is possible to use the leading and lagging edges

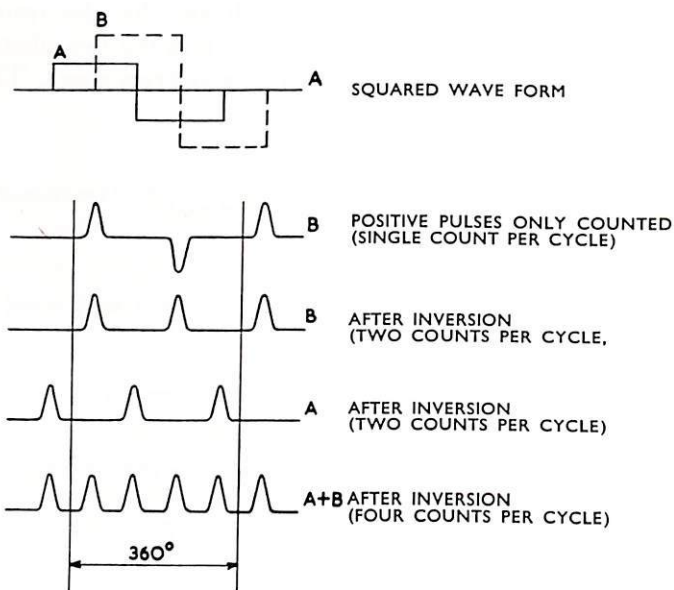


Fig. 35

Subdivision by 2 and 4 of the outputs from an optical resolver

of one phase to provide two outputs for each slit on the scale, since once again there is a definite relationship between the two signals that are reversed with the reversal of rotation (see Fig. 36). By this procedure it is possible to produce four counts per line on the scale.

ZERO REFERENCE FOR RESOLVERS

It is a simple matter on individual slit detecting optical resolvers of the type shown in Fig. 2 to provide a single reference line which has a separate detector for zero indication. On high-resolution scales where a number of lines have to be observed to obtain sufficient light, it is not satisfactory to use a uniformly spaced section of grating to provide more light, since this produces a signal in the form shown in Fig. 36. This signal has a peak difficult to determine and so non-uniformly spaced lines are used when there is only one

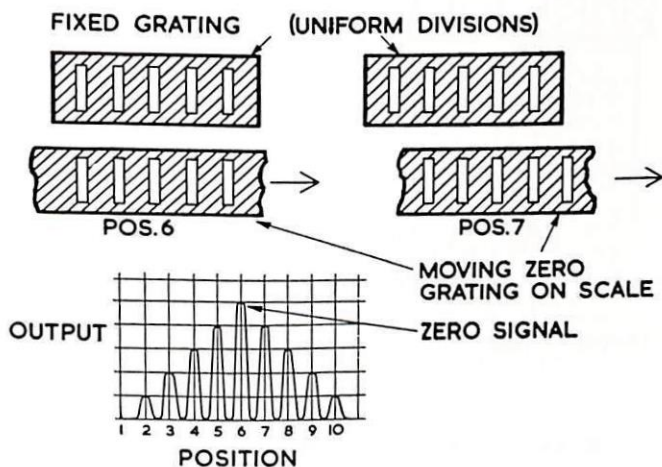


Fig. 36
Output from equispaced line gratings

position where more than one pair of lines coincide. At this point alone there is a very marked increase in the signal level. The ratio of this to smaller signals depends on the number of slits that can be observed (see Fig. 37).

The zero reference signal is used to reset the whole count

to zero or to correct the counter should it miscount. On very high resolution circular scales or long linear scales, several of these reference marks may be incorporated like milestones to keep a check on the counter.

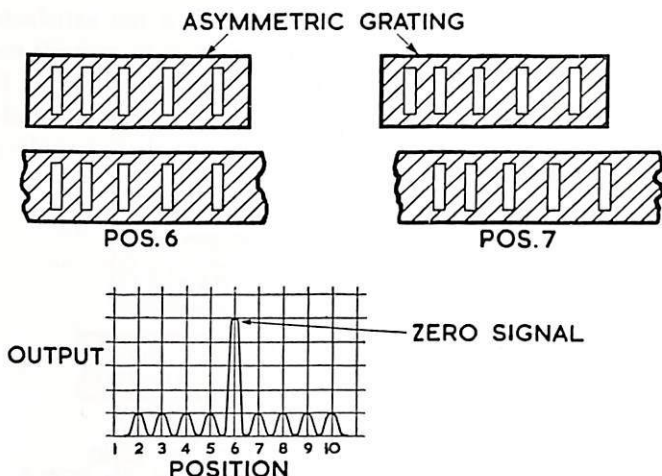


Fig. 37

Output from asymmetric gratings with an equal number of lines

REVERSIBLE COUNTERS FOR RESOLVERS

Binary and decimal electronic counters developed by various research and industrial concerns will operate from two input lines, one input driving the counter so that it adds and the other so that it subtracts. Binary counters can be made to reset themselves from a reference or zero input and such counters are not too difficult to devise. It is more difficult to design a satisfactory reversible and resettable decimal counter.

CYCLIC BINARY TO STRAIGHT CODE TRANSLATOR
FOR DIGITIZERS

Cyclic permuted codes such as the C.P.B. and the W.R.D. can be converted to their arithmetic form by the inversion rule referred to on page 20. A parallel operated relay system is shown in Fig. 12 and Tables I and II indicate the resulting

No.	CYCLIC BINARY	BINARY 8.4.2.1.
0	0000	0000
1	0001	0001
2	0011	0010
3	0010	0011
4	0110	0100
5	0111	0101
6	0101	0110
7	0100	0111
8	1100	1000
9	1101	1001
10	1111	1010
11	1110	1011
12	1010	1100
13	1011	1101
14	1001	1110
15	1000	1111

Table I

No.	W.R.D.	2.4.2.1.
0	0000	0000
1	0001	0001
2	0011	0010
3	0010	0011
4	0110	0100
5	1110	1011
6	1010	1100
7	1011	1101
8	1001	1110
9	1000	1111

Table II

outputs for C.P.B. and W.R.D. relay operated conditions. Equivalent circuits using valves or transistors can be designed easily. Serial rectifying systems are often very simple and need only comprise a two-state switch or flip-flop controlling a gate set one way by the appearance of a 1 and returned by the appearance of the next 1 and so on. Fig. 38 gives a diagram of this arrangement. It is assumed for explanation purposes that the digitizer presents C.P.B. code in parallel form although it is possible to design digitizers giving serial

output. The flip-flop is conditioned by the digitizer output and switches over each time a 1 appears. The gate inhibits the clock pulse when the flip-flop is in the condition shown and passes it (representing a 1) when it is in the opposite condition. For each sampling pulse received from the clock, the scanner moves on one position.

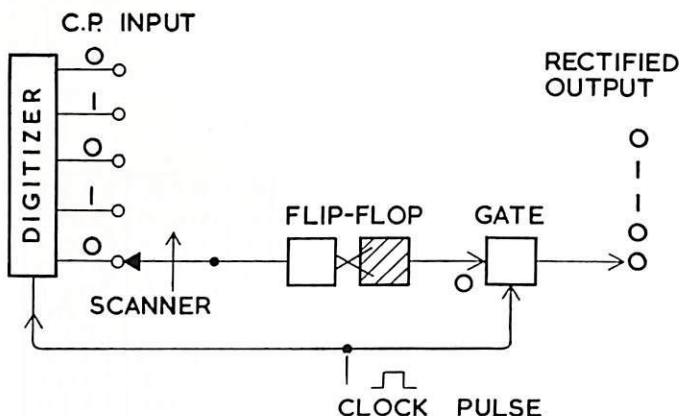


Fig. 38

Serial rectification of cyclic codes by a single flip-flop arrangement

WATTS REFLECTED DECIMAL DECODER FOR DIGITIZERS

The unit that translates the code to decimal form is known as a decoder and its simplest form is the relay tree (Fig. 39). The circuit for one of the decades of a relay tree is shown in Fig. 40. One section of the decoder provides a ten-line output labelled 0 to 9 and a second section provides an output only when there is an odd number. This output operates a relay E (odd-even) which reverses the input to the following

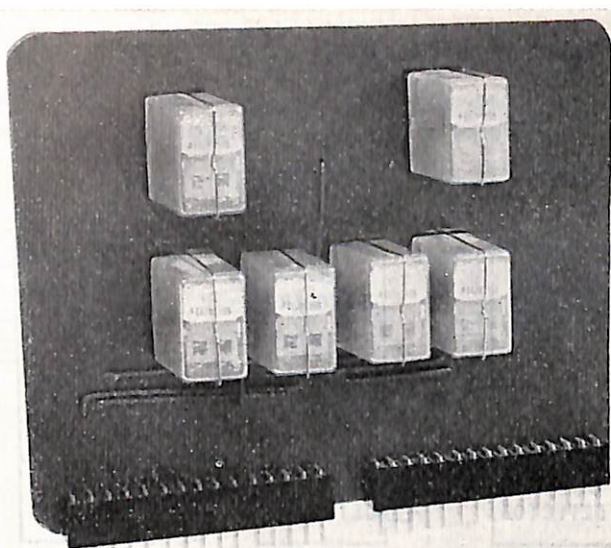
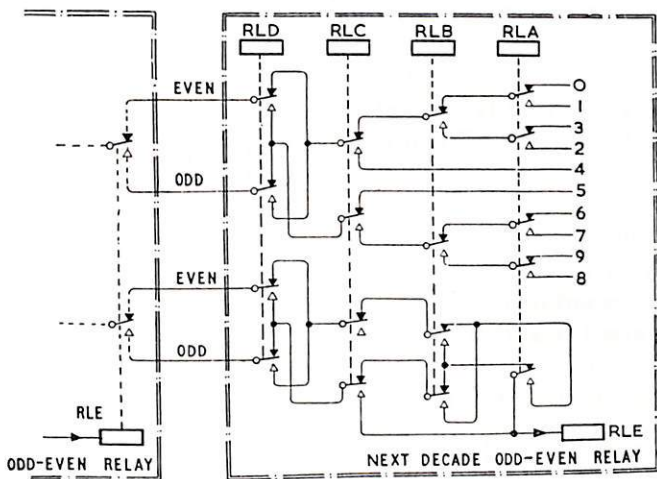


Fig. 39
W.R.D. to decimal relay decoder plate



COMPLEMENTING OR REVERSAL OF OUTPUT OCCURS WHEN PREVIOUS HIGHER DECADE READING IS ODD

Fig. 40
Relay tree providing decimal output and odd indication from W.R.D. code

decade tree (Fig. 41). This has the effect of reversing the 0-to-9 line output or complementing on 9, thus satisfying the inversion rule for rectifying cyclic codes.

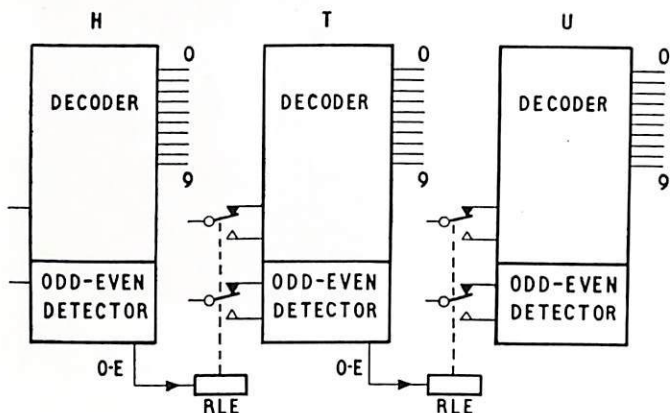


Fig. 41

A three-decade decoding arrangement for W.R.D. code

DIGIT STORES FOR DIGITIZERS

Fig. 42 shows a typical relay store which is used with mechanical digitizers. When interrogation takes place, an actuating relay completes the circuits to the scale of the digitizer for a few milliseconds in transit and then breaks them. Completed circuits represent 1 and cause the appropriate coils to be energized and their hold-on contacts to close. The actuating relay and the energized store relays remain energized via their hold-on contacts, all the store coils having been disconnected from the digitizer scale. This operation prevents the unenergized store relays (0's) from being energized when the scale is moved. Breaking the supply line drops all relays out.

In optical-digitizer systems, stores are usually valve or

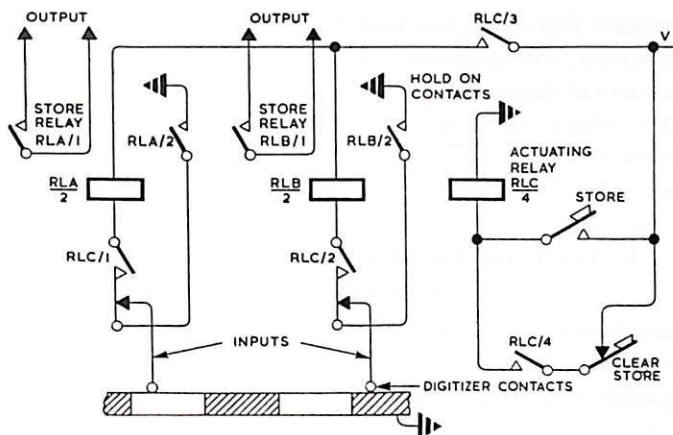


Fig. 42

Circuit diagram showing two relay stores for use with digitizers

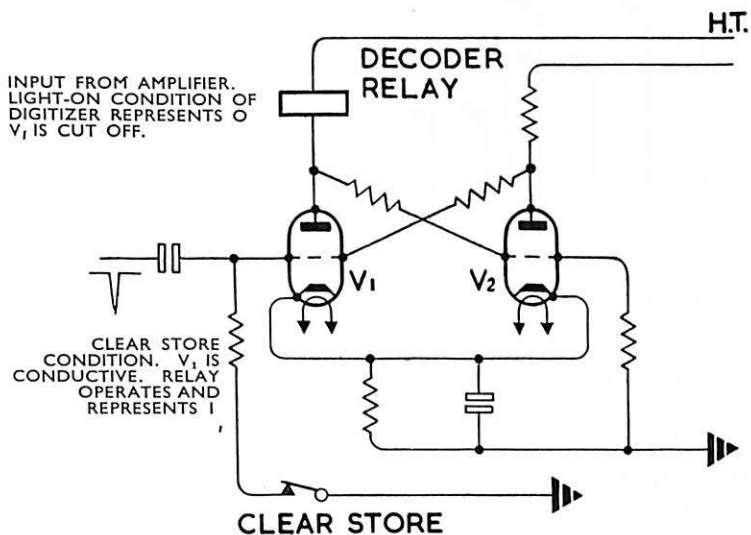


Fig. 43

Circuit diagram of a valve flip-flop store

transistor flip-flops, but may be transistor avalanche diodes, thyatrons, or magnetic cores. These may be used with mechanical digitizers. In many instances, the stores operate relays which provide power drives for solenoid operated typewriters, punches, etc. These relays may be the decoder relays. Fig. 43 shows a valve flip-flop store arrangement.

OUTPUT-DRIVE AND PARITY-CHECK RELAYS FOR DIGITIZERS

The relays of an output-drive unit are operated by an amplifier or store and provide power switching. If, for example, the code is W.R.D., there will be four relays per decade. A

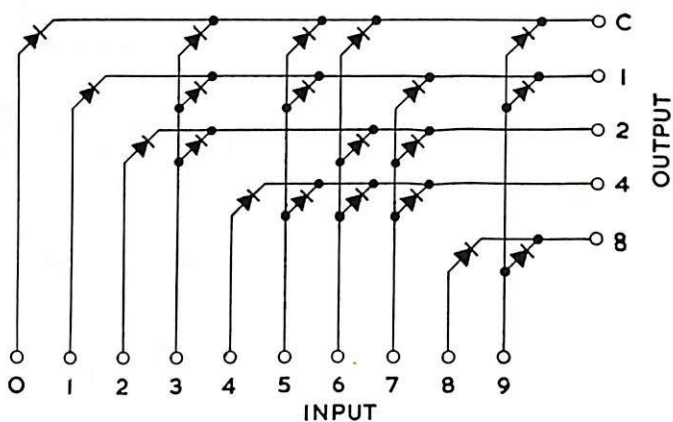


Fig. 44

Diode matrix encoder circuit for decimal to Ferranti code
(1, 2, 4, 8 and parity check)

checking or parity circuit is wired through extra contacts on the output relays and these contacts indicate when a relay is not working or operates out of turn. This is because its arrangement provides for an additional output whenever an

even number of output relays pull in, so making the total outputs odd in number. If the outputs operate a five-hole tape, the tape should always have an odd number of holes across it for every recorded figure. Suitable detecting circuits check the tape when it is read back and if the number of holes in a group is even, the tape reading is stopped because this is an indication that a faulty recording has occurred.

DECIMAL TO BINARY CODED DECIMAL ENCODER
FOR TAPE PUNCHES

If the terminal equipment in a digitizer system is a tape reperforator, it may be more convenient to use a code of four holes such as 1, 2, 4, 8, code and parity check (Table III)

No.	8.	4.	2.	1.	C.
0	0	0	0	0	1
1	0	0	0	1	0
2	0	0	1	0	0
3	0	0	1	1	1
4	0	1	0	0	0
5	0	1	0	1	1
6	0	1	1	0	1
7	0	1	1	1	0
8	1	0	0	0	0
9	1	0	0	1	1

Table III

in preference to that of the W.R.D. The parity check is added so that the number of holes punched on the tape is always an odd number. This and other combinations are

most easily obtained from a ten-line decimal using a diode matrix (Figs. 44 and 45), which is usually inserted between

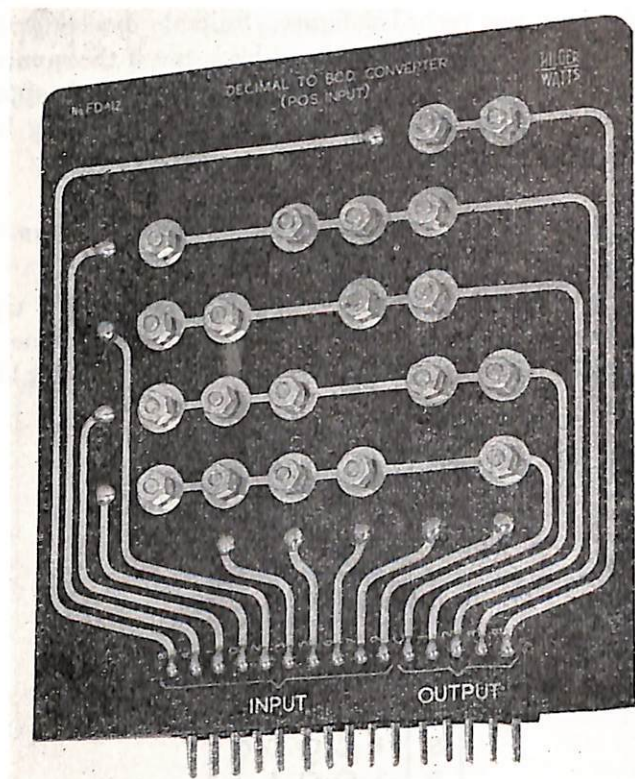


Fig. 45
Diode matrix encoder printed circuit plate

the decoder and the reperforator. For this purpose the decoder outputs are commoned and connected to the encoder input.

AMPLIFIERS FOR A.C. OPERATED OPTICAL DIGITIZERS

The outputs from neon optical digitizers are continuous or pulsed a.c. signals, and their amplitude is a few tens of millivolts. Therefore it is necessary to amplify these signals in order to operate the relays. The amplifiers are conventional

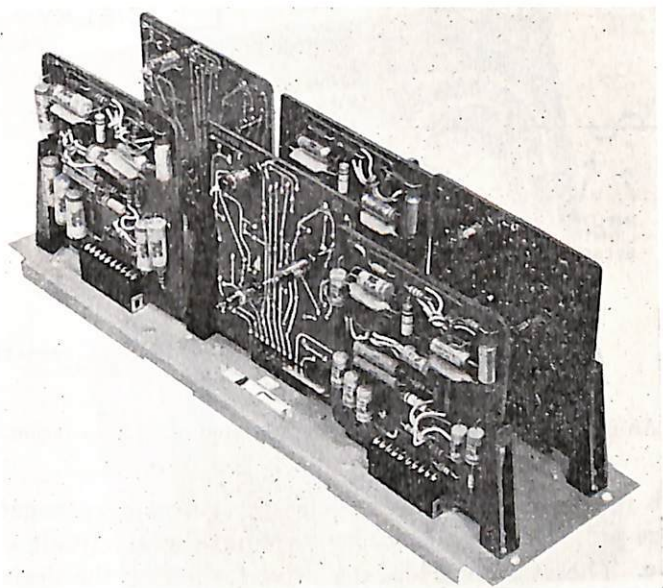


Fig. 46

Valve amplifier strip containing twelve channels used with Schwarz cell digitizers

two-stage valve types requiring no further description. A bank of twelve amplifiers (3 decades) is shown in Fig. 46.

In pulsed systems, the amplifier outputs are used to drive flip-flop stores, and diodes are provided to ensure that only the negative pulses get through to the grids of the stores.

When a continuous display is required, the neons in the digitizers are run off 50 cycles or some other convenient frequency. Since the decoder relays operate on d.c., the amplifier outputs are rectified in the circuits called integrators.

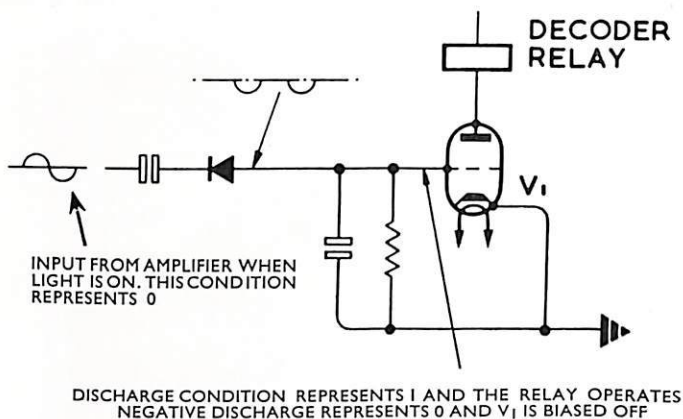


Fig. 47

An integrator amplifier circuit for continuous A.C. operation

Each integrator has a diode gate; the gate allows negative waves only to charge a capacitor in the grid circuit of a valve. The valve provides the drive for one of the decoder relays (Fig. 47).

AMPLIFIERS FOR DIRECT-CURRENT OPERATED OPTICAL DIGITIZERS

Silicon-cell digitizers which have filament light sources give out d.c. signals. In low-resolution digitizers these outputs are large enough to drive d.c. amplifiers (Fig. 49). Since the silicon cell has a relatively low impedance and is a current

generator, the most suitable amplifiers are transistors. Fig. 49 shows a conventional type of circuit with an amplifier stage and a power stage to drive a relay. In this instance, the light-off cell condition pulls in the relay.

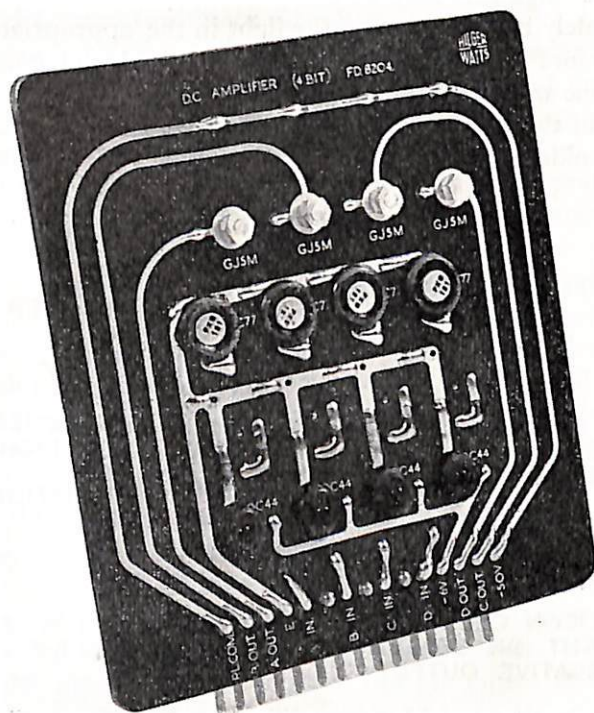


Fig. 48

Four-channel transistor amplifier plate for silicon-cell digitizers

If a pulsed or sampling system is required, the digitizer outputs may be connected to transistor switches. The

switches give a pulse output when triggered, provided the respective silicon cells are in the light and are generating.

SHARED AMPLIFIERS

Optical digitizers may be connected in parallel and selected separately by switching on the light in the appropriate unit. Therefore the outputs may be commoned and connected into one amplifier unit in a time-sharing arrangement. Since cells in the dark have high-impedance paths, back circuits are avoided and additional isolating diodes or switches are

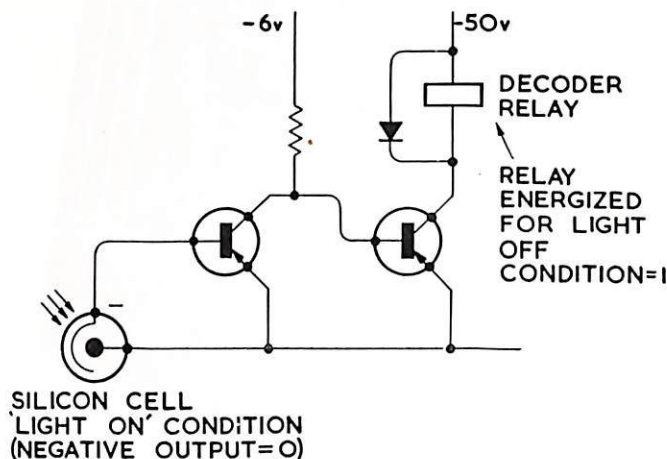


Fig. 49

A transistor D.C. amplifier circuit for silicon-cell digitizers

not required. There is, of course, a limit to the number of units that can be in parallel since each additional one reduces the effective back resistance of the cell circuits.

OUTPUT PRINTERS AND PUNCHES

The most common digital recording devices today, apart from magnetic tape recorders, are actuated by relays or solenoids and operate in serial or part-serial fashion. One exception to this is the card gang punch which operates in parallel fashion for binary recording.

Typewriters, printers, and card punches present the results in decimal form whereas tape punches and magnetic tape recorders use binary notations. The teleprinter is usually a single-line input device and operates on binary coded decimal inputs received digit by digit; storage and translation is by electro-mechanical means and the necessary equipment for this is built into the machine.

Typewriters, and card and tape punches operate in a similar fashion and accept each decimal digit in turn. The digits are recorded on the typewriter and card punch column by column while on the tape punch they are recorded line by line in code. The results to be recorded are usually held in a store or decoder and when required are collected decade by decade. Therefore some form of serializer is needed to complete the circuit for each decade section in turn.

Fig. 50 shows a typewriter arrangement with a selector or commutator bar attached to the carriage motion. All the 0-to-9 output lines from the decoder are commoned and connected to the ten solenoids of the typewriter. The three decoder inputs and commutator bar are joined and as the carriage is stepped along the decade sections are selected in turn.

The printer of Fig. 50 also has a commutator but this is coupled to the print wheels and scans differently to the typewriter. All the print wheels are rotated together and if at any time the three decimal digits set up in the decoder are

the same, the three solenoids that actuate the printing hammers will operate together. For all other combinations of figures the hammers operate at different times for each rotation of the wheels.

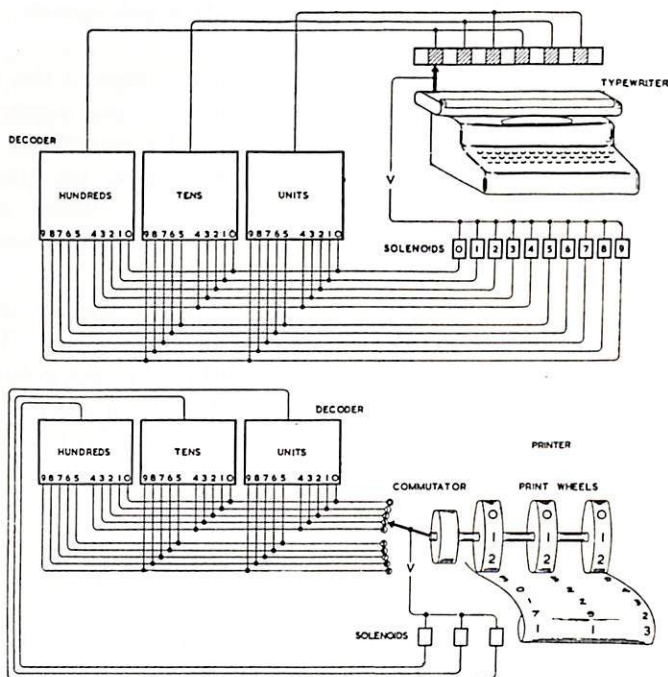


Fig. 50
Self-selecting typewriter and printer

SYSTEM ARRANGEMENTS AND APPLICATIONS

The digital equipment described in Chapters Two and Three can be applied to many systems and used in a variety of ways to suit specific requirements. One or two of the most popular arrangements and actual examples of applications will be described, but first the factors affecting the choice of equipment must be considered.

DRIVE

Digitizers and resolvers require a mechanical drive either by shaft rotation or by linear motion. If it is practicable and if the desired accuracy can be obtained, linear motion can be translated to circular motion by using a lead-screw, a rack and pinion, or a pulley. This means that the choice of scale is widened considerably since the diameter of the scale determines the digit size.

Voltages can be translated to mechanical shaft rotations with a reasonable degree of accuracy; this is done in balancing systems such as potentiometer recorders. The method is widely used because it is possible to have a pointer indication or chart record of the complete analogue.

GENERAL CONSIDERATIONS

When the characteristics of the units (such as resolution, torque, size, rate of read-out, operational life and cost) are weighed against the various requirements of a system, there are generally one or more overriding factors which decide the choice. Sometimes, however, experience is the only criterion and in such instances it is as well to consult experts. Here, as a guide, is a list of the types of digitizers and scales; a few general comments are given.

(i) *Mechanical digitizers* are suitable for slow intermittent operations where torque is available. It is best to use static read-out. The digitizer will operate relays direct. This unit requires regular maintenance.

(ii) *Neon optical digitizers* are useful for continuous rotating systems or sampling on the move where the shaft speed is not more than one revolution per two seconds. The repetition read-out rate is limited to about 25 readings per second. In time-shared systems, the selection of the digitizer is by lamp switching. Continuous read-out at 50 cycles per second can be obtained. This type of digitizer is only 3 inches in diameter and has long life and low torque.

(iii) *Flash-tube optical digitizers* have higher resolutions and read-out rates than neon optical digitizers. Examples of these resolutions and read-out rates are: for a resolution of 1 to 1000 the shaft speed is two revolutions per second and for a resolution of 1 to 4000 the shaft speed is $\frac{1}{2}$ revolution per second. These digitizers are best suited for a sampling system and their repetition rate is about 25 readings per second.

(iv) *Silicon-cell digitizers* are larger than neon optical digitizers and have very high read-out rates, for example, for a resolution of 1 to 1000 the shaft speed is possibly as much as 500 revolutions per second. They are used for very high resolution work where digit rates become very high. D.C. or pulse outputs are usual. The unit is suitable for servo systems and has a wide temperature range.

(v) *Drum digitizers* have silicon cells and so their characteristics are the same as the silicon-cell digitizer. The scale length can easily be changed by altering the diameter of the drum that carries the scale. There is no additional bearing friction as the drum is fitted to existing shafts and the rotation of the drum is limited to one revolution.

(vi) *Breakdown scales* are used to obtain maximum resolution for coded systems.

(vii) *Programmed scales* are used where precisely determined intervals need to be identified.

(viii) *Optical resolvers* give very high resolutions, but require a counter for each unit.

MODE OF OPERATION OF SYSTEMS

Systems usually fall into one of the three following categories: display, record, or control. Sometimes, however, it is useful to have a combination of two or even three of these modes.

Display usually means indication by illuminated figures such as those on projection or edge-illuminated in-line units of the type shown in Fig. 51, or on neon indicator tubes. In a

counting system it may be by Dekatron or mechanical counter drum. Typewriters and printers are also used for display purposes.

Recording normally takes the form of a solenoid-operated typewriter, line printer, tape or card punch, teleprinter, or magnetic tape recorder. One or two other devices are appearing on the market for special applications. The solenoid-operated devices are inherently slow and very often decide

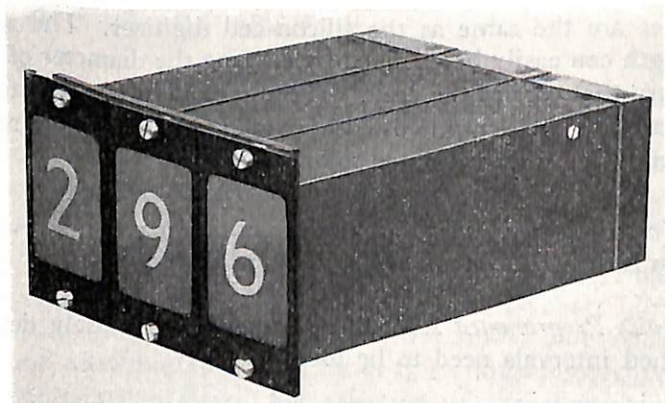


Fig. 51
A projection in-line display

the sampling rates of a data-handling system. Whilst the typewriter and printer are terminal equipment of complete systems, except where they are interposed for check purposes, the tapes and cards are provided as intermediate stores for collecting data prior to analysis by a digital computer.

Control systems usually refer to open or closed-loop servo arrangements as in machine and process control. The digital information may be derived continuously in parallel or serial form, or it may be sampled at predetermined time intervals.

Where signals are small, as in the higher-resolution devices, the sampling system is essential if drift problems in amplifiers and photocells are to be avoided.

SAMPLING RATES

The maximum rate of movement of a digitizer is governed by the time taken to extract from the scale the information in a completely coherent form. This time must be shorter than the time it takes for one digit to change, otherwise ambiguities will arise.

In a continuous read-out system providing a decimal visual display and having no storage, the limiting factor is the decoder settling time which includes any relays that are used to provide power drive for a display. If it is a balancing system searching for coincidence of numbers, the limit may be set by the coincidence actuating unit. In all events, for sensible results the digit rate cannot be faster than the sum of all the delays in the primary monitoring circuits. If the information from the digitizer is to be worked on or recorded, the scale must be stopped for the rest of the operation.

In sampling systems the digit change rate is governed by similar rules, in other words, the interrogation time. The interval between the samples is quite independent of the scale speed, the minimum time being determined by the collation of the data.

When it is not convenient to arrest the digitizer in a sampling or continuous read-out system, a fast responding short-term store is introduced. The store or photocell response time will govern the maximum velocity of the digitizer. The equipment that follows the store determines the maximum repetition rate which may be considerably longer than the sampling time.

When several digitizers are in use, it is often possible to

economize in ancillary electronics by time sharing. It will be appreciated that the interrogation time between one digitizer and the next will depend under these circumstances on the time taken to handle the stored information of each sample, since the store has to be cleared before the next sample is taken. A certain cycle of operation ensures that events take place in correct sequence.

CYCLING

Perhaps the most common method of cycling in relatively slow systems is the stepping switch or uniselector. At the other extreme cycling may be by ring counter as in some high-speed computers. The method now adopted for many of the intermediate-speed data-handling systems is the Dekatron sampling switch which operates from 50 cycles, giving about 20-millisecond operating periods for each step. This is not only reliable but silent in operation. Usually two or three tubes are used in echelon to provide the fast and slow repeating cycles.

SCHEMATIC ARRANGEMENTS

(i) *Continuous read-out.* The simplest arrangement is that of a mechanical digitizer giving a display after decoding

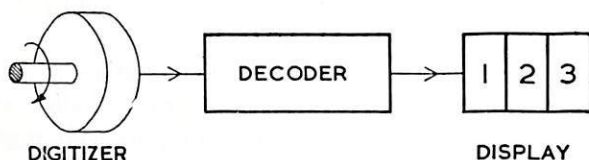


Fig. 52

A single-channel continuous read-out system

(Fig. 52). Some decoders are dual channel and the second channel output can be used to operate a typewriter, printer,

or card punch direct (Fig. 53). Decoders giving one output only can be arranged to record as well as display by switching the output lines in a time sharing system (Fig. 54).

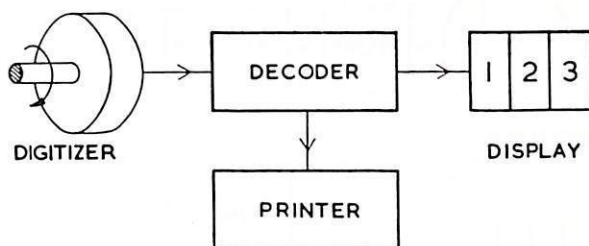


Fig. 53

A dual-channel continuous read-out system

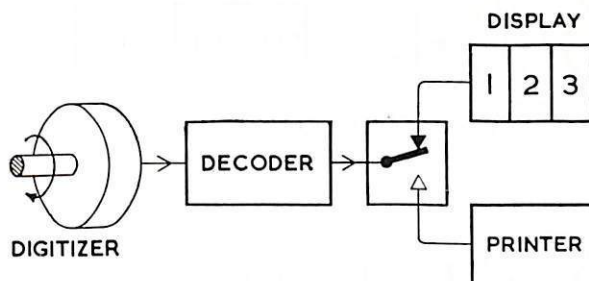


Fig. 54

A single-channel selected output system

(ii) *Sampling.* In the examples given above the digitizer must remain at rest during the recording period. If this is not convenient, a store must be interposed between the

digitizer and decoder (Fig. 55). In schemes involving an optical digitizer, amplifiers are required immediately following the digitizer (Figs. 56 and 57).

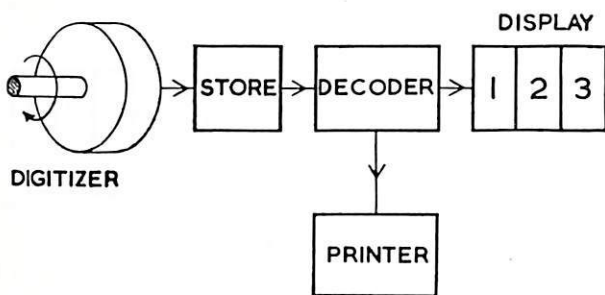


Fig. 55

A dual-channel system with a sampling and storage system

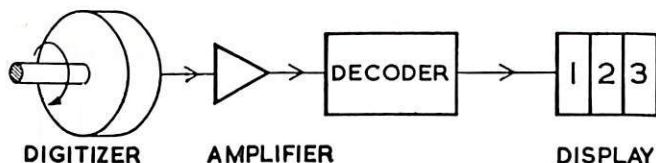


Fig. 56

A single-channel system for optical digitizers

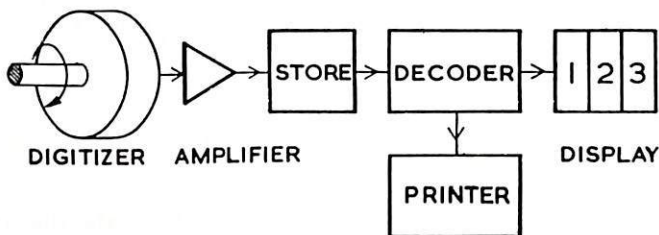


Fig 57

A dual-channel sampling system for optical digitizers

(iii) *Serializing*. Tape punches and tape recorders, unlike certain typewriters, card punches, and printers, are unable to scan or serialize the information presented to them, and so a separate cycling unit is required. Furthermore, the most common tape machines have less than ten punches or writing heads and a decimal number has either to be recorded on

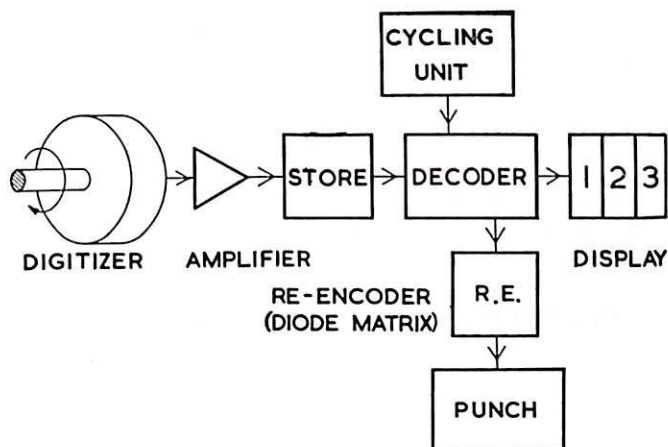


Fig. 58

A time-shared optical system giving decimal and coded outputs

two consecutive rows on the tape or to be expressed in binary coded decimal, one row of holes being required for a decimal digit. If this code is not digitizer code, it is simpler to keep to a standard decimal decoder and convert the decoder output into the desired form by means of a diode matrix converter (Fig. 58).

If the tape is fed to a computer which can be programmed to accept W.R.D. code, as is normally the case, the decoder

can be dispensed with, provided no decimal display is wanted (Fig. 59).

It should be noted that in sampling systems involving stores, the function of the cycling unit is not only to select the information decade by decade for the punch, but to clear and refill the store at the appropriate time.

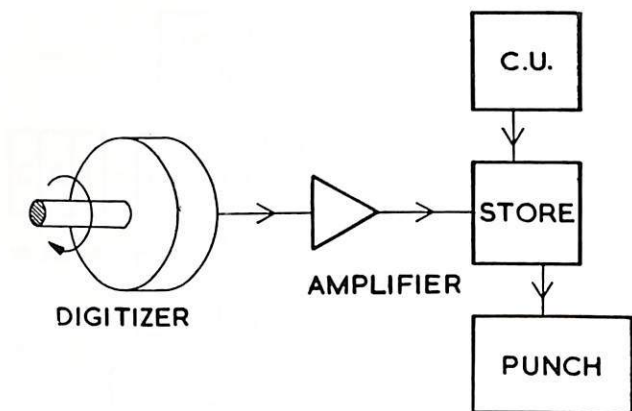


Fig. 59

An optical digitizer system recording in digitizer code

(iv) *Time sharing.* In optical-digitizer systems up to four digitizers can be coupled directly into the same amplifier unit without serious interaction, provided only one digitizer is being interrogated at a time. For the Schwarz-cell-type digitizer, selection, using a neon light source, is by switching the light of the digitizer whose read-out is required.

The same arrangement (Fig. 60) could be applied to silicon-cell digitizers, but when filament lamps are used, lamp switching imposes a delay which in many applications may be too long.

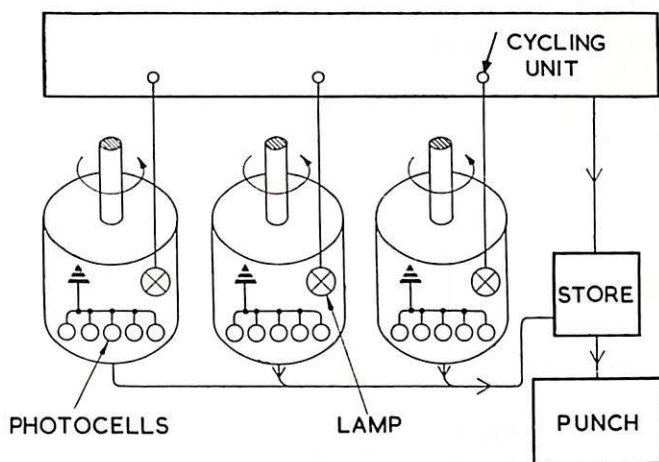


Fig. 60

Diagram to show digitizer selection by lamp switching

(v) *Presetting.* All the foregoing examples have concerned measuring systems where the analogue inputs have been translated to digital form for display or recording purposes. It may be, however, that information is passed directly or via the recording medium to a computer for analysis and the results used to control or correct the input conditions in a closed loop system. Such details are outside the scope of this monograph.

There are many applications involving coincidence balancing control. The digitizer outputs are observed whilst being rotated or moved from the zero position and the driving force is arrested when the readings coincide with preset figures set up on dial switches, or on punched tape or card.

Coincidence detecting circuits may be applied after the

decoder, if one is required, say, for visual display of the result (Fig. 61). However, to obtain a satisfactory response time the decoder needs to be a valve or transistor type.

A considerable saving in coincidence circuitry is obtained if the preset switches are arranged to produce the same code

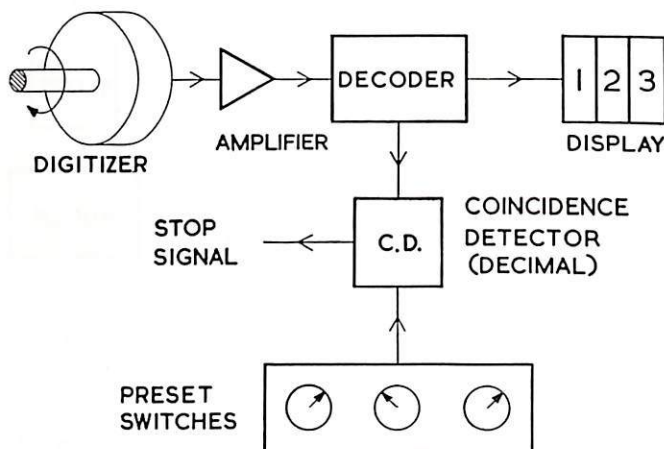


Fig. 61

A coincidence control system with decimal preset switching

as is on the digitizer scale. The visual indications on the switches can still be decimal. Also the decoder, if it is required, can be switched in on balance to prove that the balance is correct (Fig. 62).

If there is a possibility of overshoot due to the inertia of the system or failure to detect coincidence, the coincidence circuit can be supplemented by a subtractor and the result used to control approach speed and direction where reversals

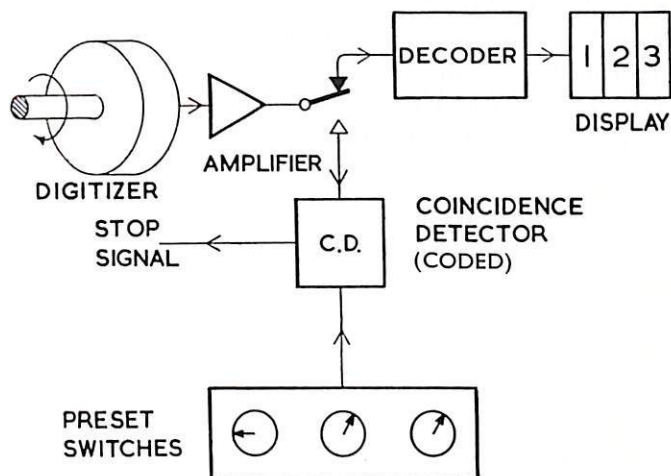


Fig. 62

A coded coincidence and decimal display system

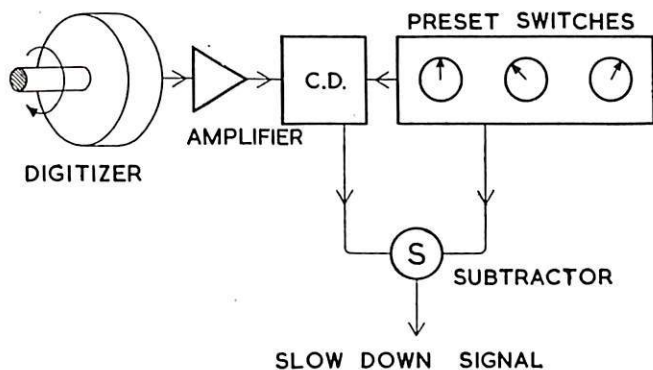


Fig. 63

A coincidence system with direction and approach control by subtraction

are possible (Fig. 63). Again it should be noted that these systems can be either continuous output or sampling, depending on the speeds, resolutions, etc., in other words, the type of digitizer involved and the characteristics of the other elements in the system as a whole.

BIBLIOGRAPHY

- Adams, A. E., Evans, D. S. and Fenner, N. G. A Recording Stereocomparator. *Trans. Soc. Instrum. Tech.*, 1960, **12**, 167-179.
- Argue, A. N. Digital Recording and Reduction in Photographic Photometry. *Observatory*, 1960, **80**, 73-74.
- Atkinson, M. P. Digital Codes in Data Processing Systems. *Trans. Soc. Instrum. Tech.*, 1957, **9**, 124-131.
- Baker, R. H. Measurement of Angle Using the Binary Digital Scale in Automatic and Manual Control edited by A. Tustin. Butterworth, London, 1952.
- Braunin, F. H. A Bidirectional Electronic Counter for Use in Optical Interferometry. *J. opt. Soc. Amer.*, 1953, **43**, 839-848.
- Brewer, R. C. The Numerical Control of Machine Tools. (In 2 parts) *Engrs' Dig.* 1958, **19**, 371-400; 1959, **20**, 5-32.
- Coales, J. F. The Application of Information Theory to Data-Transmission Systems, and the Possible use of Binary Coding to Increase Channel Capacity. *Proc. Instn. elect. Engrs, Part III*, 1953, **100**, 291-302.
- Colville, R. F. Optical Digitizers—A Review of the Position. *Automation Progress*, 1960, **5**, 258-260.
- Colville, R. F., and Fishter, G. E. A Digitized Instrument. *Hilger Journal*, 1957, **3**, 51-56.
- E.M.I. Electronics Ltd. The Application of Electronic Control to Weighing and Mixing Processes. Ref. CP87.
- Elliott, W. S., Robbins, R. C. and Evans, D. S. Remote Position Control and Indication by Digital Means. *Proc. Instn. elect. Engrs., Part B Supplement No. 3*, 1956, **103**, 437-446.
- Evans, D. S. Computers Make Sense on Scale of Two. *Engineering, Lond.*, 1960, **190**, 474-5.
- Evans, D. S. The Digitizer—A High-Accuracy Scale for Automatic Data Processing. *Brit. Comm. & Electronics*, 1957, **4**, 334-339.
- Geiser, R. D. Modern Techniques of Producing Precision Scales and Reticules. *Photogr. Engng.*, 1953, **4**, 1-11.
- Guild, J. The Interference Systems of Crossed Diffractional Gratings. Oxford University Press, 1956.
- Jones, E. M., Liffel, B., and Doering, K. M. Manufacture of Disks for Optical Shaft Digitizers. *Proc. nat. Electron. Conf.* 1955, **9**.
- Lewis, A., and Young I. R., Use of Radial Gratings in a Small Inclino-meter. *J. sci. Instrum.*, 1959, **36**, 153-157.
- Lippel, B. A Systematic Survey of Coders and Decoders. *Proc. Inst. Radio Engrs. N.Y., National Convention Record*, 1953 **1**, Part VIII, 109-119.
- Lund, G. W. ERA Shatt-Position Analogue-to-Digital Converter. *Trans. Inst. Radio Engrs. N.Y., Instrumentation Group*. 1953, P. G. 1-2, 55-64.

- Mills, A. E. S. Analogue/Digital Converters. *B.S.I.R.A. Report No. M40*, 1959.
- Mitchell, A. L. Photoelectric Analogue-to-Digital Converters. *Electronic Design*, 1956.
- Nettel, D. F. The Control of On-Off Servos by Coded Commutators. *Instrum. Pract.*, 1956, **10**, 128-132.
- Peck, E. R. and Obetz, S. W. Wavelength or Length Measurement by Reversible Fringe Counting. *J. opt. Soc. Amer.*, 1953, **43**, 505-509.
- Richards, R. K. Arithmetic Operations in Digital Computers. Van Nostrand, London, 1955.
- Roberts, T. A Shaft Position Digitizer using Synchros. *Trans. Soc. Instrum. Tech.*, 1961, **13**.
- Scholes, J. F. M. The Automatic Handling of Experimental Data in Wind Tunnels. *Brit. Comm. & Electronics*, 1957, **4**, 604-611.
- Susskind, A. K. (ed) Notes on Analogue-Digital Conversion Techniques by Staff Members of Servomechanisms Laboratory M.I.T. Technical Press and John Wiley & Sons, Inc., New York, and Chapman & Hall Ltd., London, 1958.
- Tucker, R. H. and Evans, D. S. A Digitized Measuring Machine for Determining Stellar Declinations. *Hilger Journal*, 1958, **5**, 26-29.
- White, G. S. Coded Decimal Number System for Digital Computers. *Proc. Inst. Radio Engrs., N.Y.*, 1953, **41**, 1450-1452.
- Young, J. F. A Transistor Characteristic Curve Tracer. *Electron. Engng*, 1959, **31**, 330-336.
- Younger, A. S., Mallett, E. S. and Morgan, G. C. Data Reduction for Guided Weapon Trials at Aberporth. *Trans. Soc. Instrum. Tech.*, 1960, **12**, 61-71.

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